

DOCUMENT No. 606-I

MARS SCIENTIFIC MODEL

(NASA-CR-130711) MARS SCIENTIFIC MODEL,
VOLUME 1 (Jet Propulsion Lab.) 611 p

N73-71413

00/99 Unclass
62715

VOLUME I

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

MARS SCIENTIFIC MODEL

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March 1, 1972

FRONTISPIECE

Photograph of Mars taken by R. B. Leighton of the California Institute of Technology on August 24, 1956, eighteen days before opposition. The planet was approximately 35.2 million miles from Earth at the time the photograph was obtained. Mare Cimberium and Mare Tyrrhenum dominate the center of the disk, and Syrtis Major is at the far left. The season is late spring in the southern hemisphere (north is at the top). The Mt. Wilson 60-inch reflector was used and its aperture was cut to 21 inches with an off-axis diaphragm; exposure time was 20 seconds on Kodachrome Type A film. The positive, used in making the print, was composed by the Jet Propulsion Laboratory. (The repeated copying of this photograph in the reproduction processes has greatly decreased the clarity of surface detail and has caused the yellowish tones of the original positive to appear orange here.)

PREFACE

Our intent in the new edition of this document has been to present a summary of knowledge about Mars shortly before the time of arrival of Mariner 9. Emphasis has been given to observational results, with a limited amount of interpretation where appropriate. Two sections (5.3 and 5.4) have been retained from an earlier edition. The data reflected in Sections 5.3 and 5.4 is nearly 5 years old and should be utilized solely as background information until later data has been derived. It is suggested that the interested reader may obtain later data by reference to the Atmospheres Section of Viking '75 Project, Mars Engineering Model. Two new Sections, 4.3 and 5.5, Secular Change and Atmospheric Circulation respectively, may be supplied at some future date.

Material in this document has been reviewed extensively both by Jet Propulsion Laboratory Scientists and by other specialists. Some errors seem inevitable, however, and the authors will be grateful for comments, corrections, and criticism from our readers. Each page shows the date of the latest information and identifies the author or authors of the material on that page.

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ACKNOWLEDGMENTS

Contributions from widely diversified scientific disciplines were necessary to compile this document. The cooperative spirit of the many individuals contacted, both on and off the laboratory, is greatly appreciated. Although the document has been almost completely rewritten since the 1968 edition, something of the spirit and contributions of Mrs. J. Negus de Wys have come through from that earlier version.

Special thanks are due to James Roth for reviewing the drawings made after Mariner 6 and 7 TV pictures. Grateful appreciation is extended to the following investigators who kindly sent Preprints of important papers which were very useful in the preparation of some of the sections (indicated in parentheses): D. L. Anderson (2); T. C. Hanks (2); G. Neugebauer and E. Miner (3.1); A. B. Binder and J. C. Jones (3.2 and 3.4); R. Goldstein (3.3); G. C. Pimentel (3.4); R. E. Arvidson (3.5); A. B. Binder (3.5); W. K. Hartmann (3.5); G. E. McGill and D. U. Wise (3.5); C. H. Thorman and G. G. Goles (3.5); A. Woronow and E. A. King (3.5); W. A. Baum, C. F. Capen, and L. J. Martin (4.1 and 4.2).

We also wish to thank our many colleagues who spent much valuable time carefully reviewing individual sections of the document. Their contributions to improve accuracy and clarity have been a great asset to us.

TOPICAL SUMMARY

The Mars Scientific Model, which is intended to be a source of the most recent and accurate data for Mars spaceflight program needs, is organized to provide the user with the means for convenient and expedient location of desired information and also to facilitate updating. The following order of subject matter appears in each section (or subsection) as applicable: Introduction, Data Summary, Discussion, Conclusions or Implications, Figures, Tables, and Bibliography. Some sections also contain a Glossary and/or Appendices. Each section can be considered a separate entity but can also be used in conjunction with other correlated sections of the document. Each of the six main sections contains a detailed Table of Contents, List of Illustrations, and List of Tables for the material contained within the respective section. This Topical Summary identifies the primary content of material contained within the appropriate section or subsection.

SECTION

TITLE AND CONTENT

1. ORBITAL AND PHYSICAL DATA

Historical review of Mars orbit theories and ephemerides. Orbital elements, related constants and derived data. Earth-Mars distances. Rotational elements and derived quantities. Precession the axis. Physical data summary. Seasons. Calendar (Norton, 1967). Satellites Phobos and Deimos: orbital and physical data. Astronomical glossary.

2. INTERIOR

Shape of planet: geometrical, dynamical and optical flattenings. Gravitational potential and coefficient J_2 . Moments of inertia. Gravity formula of Clairaut. Hydrostatic flattening approximation of Radau-Darwin. Density models: historical and recent (Binder, 1969; Anderson, 1972). Thermal history: background and recent models (Hanks and Anderson, 1969).

3. SURFACE

3.1 Thermal Properties. Theoretical temperatures derivable from insolation. Atmospheric effects on Mars. Thermal models (Leighton and Murray, 1966; Kieffer, 1971). Infrared radiometry. Temperatures observed from Earth. Temperatures observed from Mariner 6 and 7 spacecrafts. Microwave radiometry. Disc brightness temperatures observed from Earth.

3.2 Ultraviolet, Visible, and Infrared Properties. Photometry and photometric systems in astronomy. Reflection versus emission from Mars. Integrated photometric properties of Mars: total brightness, average color, phase function, Bond albedo,

and geometric albedo. Detailed photometry theory: radiance coefficient, radiance factor, photometric function, normal albedo. Results of detailed photometry of Mars: table of regional spectral albedos (Binder and Jones, 1972). Polarimetry: theory and results for Mars. Glossary of photometry and polarimetry.

3.3 Radar Properties. Radar astronomy: basic theory and observational techniques. Radar cross section and reflectivity. Angular backscattering and surface roughness (average slopes). Topography from ranging. Results for Mars. Correlation.

3.4 Chemical and Physical Properties. General physical and chemical properties expected for the Martian ground. Earth-based reflectance spectra of dark areas and bright areas, with interpretations. Goethite stability on Mars. Adsorption of volatiles: carbon dioxide and water vapor experiments. Permafrost speculations. Chemical composition of the polar caps. Mariner 7 IRS spectra of the South Cap. Ozone observation. Carbon dioxide clathrate hydrate: speculations.

3.5 Morphology and Processes. Photographic report of Mariner 6 and 7. Topography obtained by Earth-based radar and the Mariner 6 and 7 UVS and IRS. New global (Mercator) maps of Mars, with lists of names. Regional and polar maps. Morphology of terrain types observed by the Mariners: cratered, chaotic and featureless terrains. Crater statistics and analyses, from Mariner 4 and Mariner 6 and 7 photography separately. Crater modification processes. Ages of large craters: speculations. Chaotic terrain: distribution, and speculations on age, origin and processes. Featureless terrain: speculations of age and origin of Hellas basin and processes on its floor. South Polar Cap: photography by Mariner 7. Morphology and processes of the 3 zones recognized: margin or edge, interior, and central region. Thickness and permanence of frost cover. Dark and bright areas: Meridiani Sinus region boundaries and markings observed by Mariner 6 and 7. Canals, lineaments and oases in the Mariner photography.

3.6 Mariner 1969 Photographic Atlas of Mars. Mariner 6 and 7 Television Experiment design. Camera system. Image processing. Far Encounter pictures: a commented selection. Near Encounter pictures: a commented selection grouped under 5 categories: Cratered Terrain, Chaotic Terrain, Featureless Terrain, Atmospheric Hazes, and South Polar Cap. Photoference Data Tables for all 200 pictures taken.

4. OBSERVATIONAL PHENOMENA

4.1 Clouds and Hazes. Violet layer and blue clearings. Blue Clouds. White clouds and hazes. Yellow clouds and dust storms. Gray clouds, and bright spots or flares.

4.2 Seasonal Activity. Polar caps. Polar hoods. Dark polar fringe. Seasonal evolution of the caps: boundaries and regression curves. Seasonal behavior of clouds. Recurrent white clouds. Major yellow clouds or storms. Whitening areas. Surface features: wave of darkening and seasonal behavior. Charts of local seasonal changes in equatorial, northern, and polar areas. Global colored maps of seasonal activity of surface, with overlays for clouds, possible frost, and wave darkening.

5. ATMOSPHERE

5.1 Atmospheric Composition. Observed constituents: carbon dioxide, carbon monoxide, water vapor. Carbon and oxygen isotopes, dissociation and ionization products (in upper atmosphere), ozone (over polar cap). Assumed constituents and upper limits. Units used for atmospheric abundances.

5.2 Surface Pressure. Historical results using photometry or polarimetry; critique of the assumptions. Spectroscopic methods and results. Spacecraft radio occultation method and results of Mariner 4, 6 and 7. Mean surface pressure, seasonal and topography effects.

5.3 Lower Atmosphere. Layers of the lower atmosphere. Physics of the troposphere, stratosphere, and mesosphere. Convective, radiative, and convective-radiative models. Models I, II, and III.

5.4 Upper Atmosphere. Layers of the upper atmosphere. Physics of the photodissociation region. Physics of the ionosphere including ionization processes and thermal processes. Preliminary E-Model. F_1 -Model. F_2 -Model.

6. CIS-MARTIAN MEDIUM, RADIATION

Solar electromagnetic radiation at Mars: total irradiation (solar constant) and spectral distribution (solar spectral irradiance). Extreme ultraviolet, X-rays, and radio wave radiation components. Absorption in the Martian atmosphere. Solar particle environment at Mars: solar wind (protons, alphas, electrons), solar cosmic rays or flares (protons). Galactic cosmic rays. Induced charged particle flux (from atmospheric collisions). Solar interplanetary magnetic field. Martian magnetosphere, magnetic moment, and surface magnetic field. Meteoroid environment: sporadic and stream meteoroids. Fluxes and velocities.

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1. ORBITAL AND PHYSICAL DATA

INTRODUCTION

This section discusses the Orbital and Physical Data for Mars and the Martian Satellites Deimos and Phobos.

The discussions are organized into two subsections; the first, 1.1, deals with the planet Mars while the second, 1.2, deals with the known data covering the satellites.

1.1 MARS - ORBITAL AND PHYSICAL DATA

Historical Background

The planet Mars holds a special place in the origin of celestial mechanics, for it was through the study of its orbital motion, from the positional data gathered by his master Tycho Brahe, that the young Kepler discovered the three laws of planetary motion which bear his name. (The first two laws were announced in his *Astronomia Nova* published in 1609, while the third law appeared in 1618.) It was by generalizing these empirically discovered laws that Newton, with remarkable insight, was able to enunciate in 1687 (in the *Principia*) the Law of Universal Gravitation, which forms the basis of celestial mechanics. At the same time, he also formulated the three laws of motion, the basis of modern dynamics. The problem of the motion of two bodies under the inverse square law of gravitational attraction was solved by Newton (yielding the Keplerian ellipse). However, the real problem in dealing with motion in the solar system is that of n bodies under mutual attraction. This problem is far more difficult, and in fact the simpler "three-body problem" has not been solved in its general form. Only special cases of little value to the solution of the planetary or lunar motion problems are completely integrable. The standard procedure in planetary theory is one of successive approximations of the orbit by the general perturbations method. The planet's motion (a disturbed ellipse) is treated in terms of "perturbations," or deviations from Keplerian elliptic motion around the Sun, under the disturbing attraction of another planet, and thence of all other planets. The analytical expressions obtained (called "general perturbations") - which usually give the variation with time of six variables known as "orbital elements" defining the orbit and position of the planet - are found to contain two classes of terms: (1) "secular terms," which change very slowly but proportionally with time (t), although their sum remains bounded* (except for very long term dissipative forces), and (2) "periodic terms," which are series of sine and cosine terms, involving different short periods, where time (t) is again the independent variable. Needless to say, these expressions are complicated because the infinite series are truncated only after many terms, so as to furnish more accurate results. The analytical methods employed for the solution of the lunar and planetary

*It was shown by Lagrange and Laplace that these secular terms actually have extremely long periods (thousands of years).

problems were devised primarily by the mathematical astronomers of the 18th century, initially, Euler, Clairaut, and D'Alembert, followed by Lagrange and Laplace. The ephemerides, or tables of the planet's positions at regular time intervals, derived from planetary theory as comprehensively developed by Laplace, however, were of insufficient accuracy (for many navigational or astronomical purposes) when compared with actual observations. Although inaccurate, Lindenau's (1811) Tables, or deLalande's (1792) Tables for Mars were definitely superior to Halley's (1749) earlier tables. Consequently, planetary theory required improvement, which was accomplished in the 19th century initially by Hansen, and Leverrier, with refinements by Hill and Newcomb. This often meant new approaches (Hansen's method of treating perturbations), or major overhauls (Newcomb's introduction of a uniform system of astronomical constants, such as planetary masses) (Newcomb, 1895). The resulting improved tables which appeared for Mars were those of Leverrier (1861) and the more accurate tables of Newcomb (1898). In the early part of the 20th century, observations showed that Newcomb's orbit for Mars was still unsatisfactory. Indeed, Newcomb had neglected the second order perturbations, due mainly to the attractions of Earth and Jupiter, and also due, in lesser degree, to Venus and Saturn. The empirical corrections given by Ross (1917) did not significantly improve the situation. A new theory of Mars was then constructed by Clemence, who used Hansen's method (which Hill had found so successful in treating Jupiter and Saturn). The new theory included the previously neglected second-order terms, and some third-order terms, when it appeared in its complete form in 1961 (Clemence, 1949, for first-order theory, and Clemence, 1961, for second-order theory). The great accuracy of the new theory, about 0.04 arc seconds difference between observed and predicted longitudes of Mars, warrants the issuance of much more reliable ephemerides of Mars in future volumes of The American Ephemeris and Nautical Almanac. At the present time, this publication still calculates the Mars positions according to Newcomb's old theory, supplemented by Ross' corrections. However, the U.S. Naval Observatory has issued (until final adoption of Clemence's work) provisional ephemerides of Mars for the 1800-2000 period (Duncombe, 1964, for 1800-1950 period, and Duncombe and Clemence, 1960, for 1950-2000 period).

The last two decades have witnessed three revolutionary developments in engineering which permitted rapid improvement of our knowledge of the solar system through applied celestial mechanics. These are

- 1) High-speed digital computers.
- 2) Spacecraft.
- 3) Radar astronomy.

With the new computers, it is now possible to perform (without undue labor) the step-by-step numerical integration of the differential equations of (disturbed) motion of any planet along its orbit. This was first done for Mars by Herget to test Clemence's theory, but is now performed routinely, to derive new ephemerides of ever-increasing accuracy, using all data available (i.e., optical, spacecraft, and radar data). With radio tracking of spacecraft flying past Venus and Mars, and the radar bounce experiments on these planets, the

precise measurements of their distances and velocities have become available, as well as their masses and, with lesser accuracy, their radii. It is now possible to follow Mars by radar around its entire orbit. Therefore, in a few years, we can expect another revision of the theory of Mars motion through modern analytical and computational methods of celestial mechanics.

JPL Ephemerides

In recent years, necessity and the data obtained from spacecraft and radar exploration of the nearby solar system (Moon, Venus, Mars, Mercury), coupled with the availability of high speed computers, have prompted JPL to produce its own lunar and planetary ephemerides. The JPL ephemerides are of superior accuracy to the existing publications (such as those published by the American or British Nautical Almanac Offices), which give latitude and longitude to ~ 0.1 arc seconds. The JPL ephemerides are under continual development, fully utilizing the almost continuous influx of new data from optical, radar, and spacecraft observations, as well as the latest or most advanced forms of lunar and planetary theories of motion. Thus, these ephemerides are of ever-increasing accuracy. To prevent accuracy degradation of the source data, and also permit direct use by computer programs, magnetic tape recording is used at every step. The JPL Ephemeris Tape System, established in 1964, is a collection of procedures, computer programs, and tape archives of ephemeris data used in generating the new ephemerides called JPL Ephemeris Tapes. These ephemeris tapes are prepared in sets of three, which collectively cover the 1950-2000 period. They tabulate for that period the rectangular coordinates and velocity vector components of the nine planets and the Moon, as referenced to the mean equator and equinox of 1950. They also include nutations in longitude and obliquity, and their rates, plus modified second and fourth differences of all these quantities to facilitate interpolation. The method of special perturbations or step-by-step numerical integration of the orbits is used for calculating the planetary positions and velocities, with relativity effects (as given by the Schwarzschild metric) taken into account. [Note: The special perturbations solution consists of determining the orbit as closely as possible by successive approximations ("integration fits") — through numerical integration of the second order differential equations of motion of the planets with selected epoch values to best fit the source positions by the least-squares procedure. This method is also known as 'fitted integration' of an orbit, to fit source accuracy. The source positions and theories used ultimately determine the accuracy of the ephemerides produced.]

More complete description of the JPL Ephemeris Tape System can be found in the report issued by Peabody et al. (1964). JPL ephemerides approved for external distribution ("Export Ephemerides") so far have been successively: DE 3 (Peabody et al., 1964), DE (Devine, 1967), and DE 69 (O'Handley et al., 1969). These ephemerides have been extensively tested with real data. Experimental and special purpose ephemerides are available only to JPL internal users.

Orbital Elements (See Figs. 1 and 2)

The elliptical unperturbed (or Keplerian) orbital motion of a planet around the Sun is completely determined by the six elements defined below (Fig. 2) and referenced to the ecliptic plane and the vernal equinox of Earth (Fig. 1):

a = semi-major axis (of the ellipse)

e = eccentricity (of the ellipse)

i = inclination angle of orbit to ecliptic

Ω = longitude of ascending node (Ω) of the orbit on the ecliptic, or
 $\Omega = \gamma\Omega$

$\tilde{\omega}$ = longitude of perihelion (π), measured from equinox along the ecliptic to node, then along the orbit to perihelion, or $\tilde{\omega} = \gamma\Omega + \Omega\pi'$

M = mean anomaly of planet at time t (epoch), since perihelion passage time t_0 , or $M = n(t - t_0)$, as derived from the mean daily motion $n = 2\pi/P$, where P is the sidereal period of revolution of the planet*

or

L = mean longitude of planet at time t , that is simply $L = \tilde{\omega} + M$

Since planetary orbits are never exactly elliptical because of the gravitational perturbations due to other planets and satellites, it is customary to give a mean reference orbit, valid for a limited period of time (a year or so), which sufficiently approximates the actual orbit for most astronomical purposes. Neglecting the irregularly varying "periodic" terms of the perturbations and utilizing the progressive "secular" terms of the perturbations, formulae for the "mean elements" of such an orbit, at a certain time, are available in the form of polynomials in the time variable t , which is the time interval since an epoch $t_0 = 0$. While the elements e and n (or P) vary extremely slowly with time (a is considered constant), the elements i , Ω , and $\tilde{\omega}$ are dependent upon the reference system (ecliptic and vernal equinox) and vary more rapidly. The mean elements may be referenced to either the instantaneous ecliptic and mean equinox — "of date" which is continually moving — or to a fixed ecliptic and mean equinox of a conveniently chosen epoch (such as 1950.0). The latter system is more suitable to astrodynamical applications.

*Note: From planetary theory, n is related to a by the relation $n^2 a^3 = k^2(1 + m)$, where k is the Gaussian gravitational constant, and m is the planet's mass in terms of the Sun's mass.

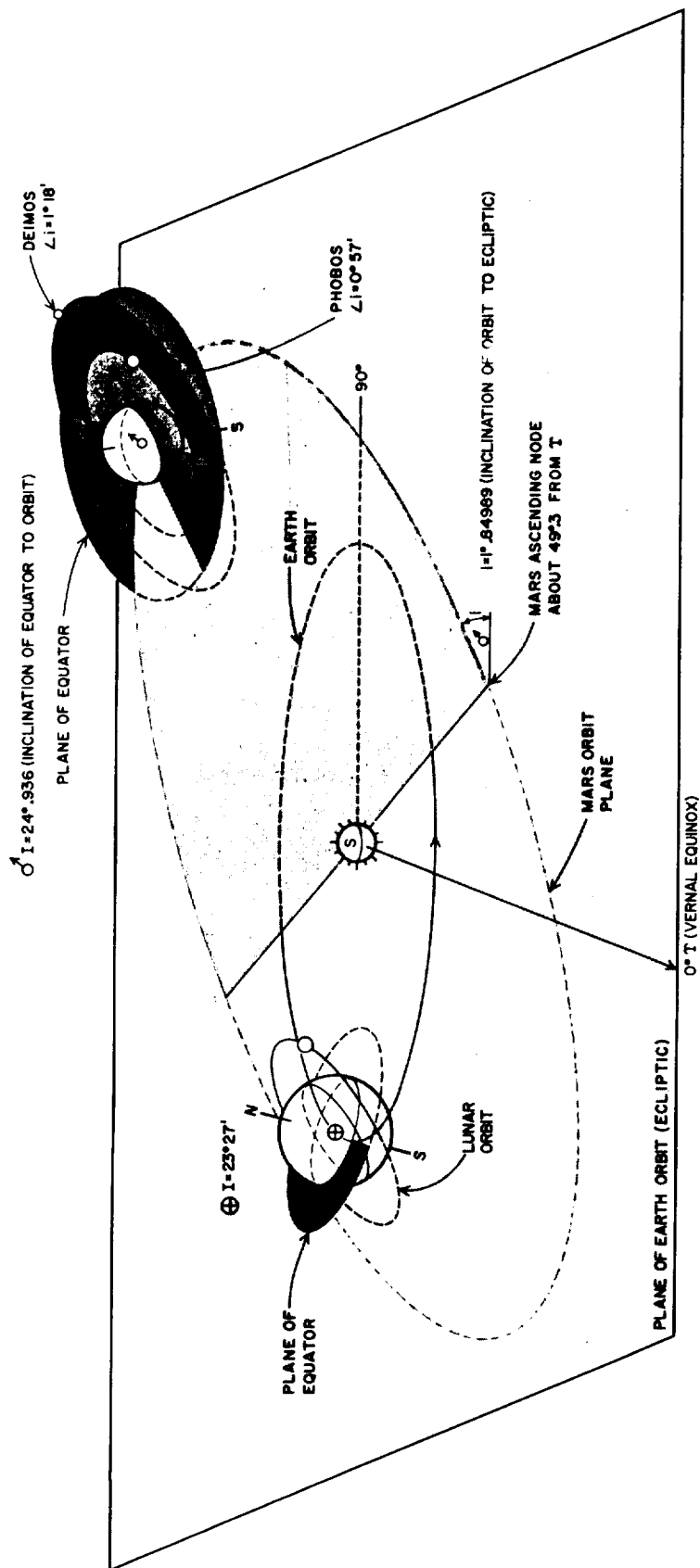


Fig. 1. The reference planes (orbit and equator) of Earth, Mars, and satellites. Angular relationships are exaggerated. At perihelic opposition the south pole of Mars is tilted toward Earth; at aphelic opposition the north pole is tilted toward Earth (de Wys, 1967).

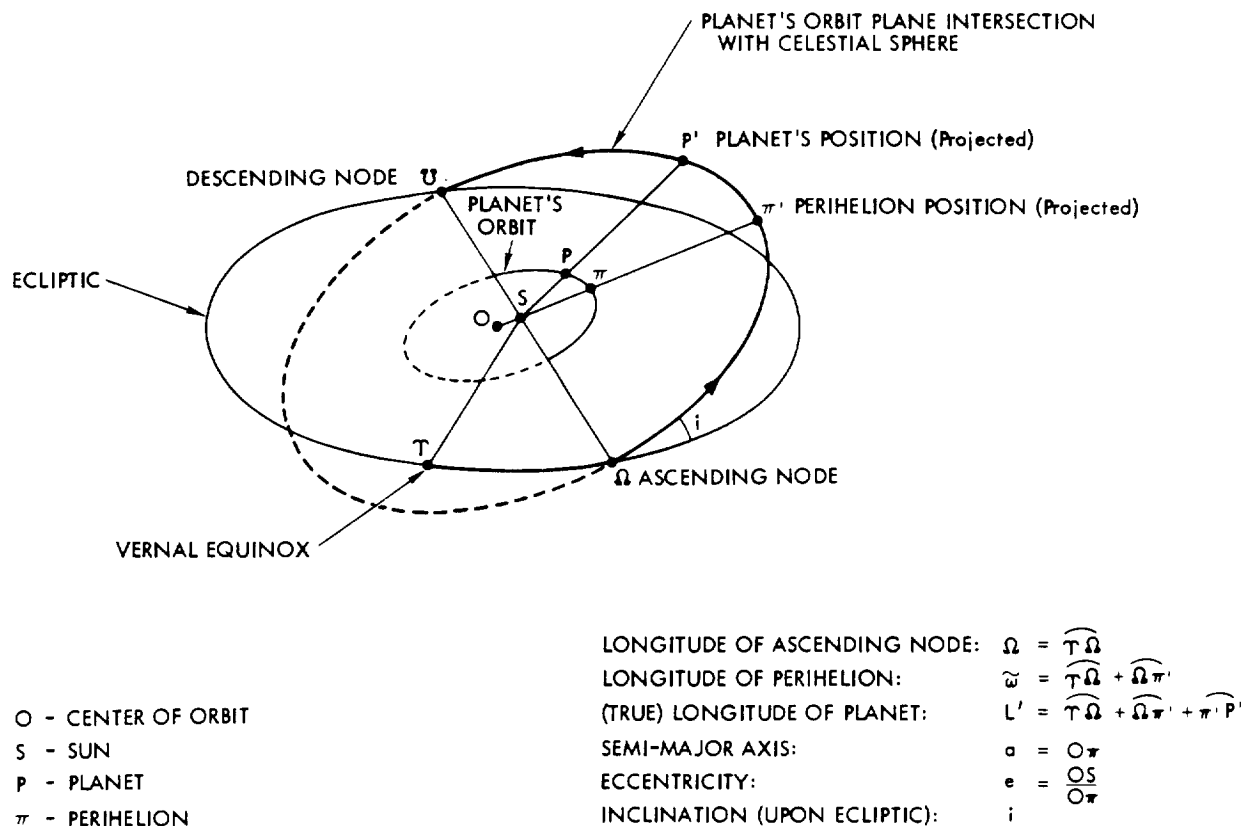


Fig. 2. Orbital elements.

Mean Orbital Elements of Mars (Figs. 1 and 2)

- 1) Referred to (moving) mean equinox and ecliptic of date (American Ephemeris, Explanatory Supplement, 1961)

$$a = 1.5236915 \text{ AU}$$

$$e = 0.09331290 + 0.000092064 t - 0.000000077 t^2$$

$$i = 1^\circ 51' 01.20'' - 2.430'' t + 0.0454 t^2$$

$$\Omega = 48^\circ 47' 11.19'' + 2775.57'' t - 0.005'' t^2 - 0.0192'' t^3$$

$$\tilde{\omega} = 334^\circ 13' 05.53'' + 6626.73'' t + 0.4675'' t^2 - 0.0043'' t^3$$

$$M = 319^\circ 31' 45.93'' + (53^r + 215490.60'') t + 0.6509'' t^2 + 0.0043'' t^3$$

$$= 319.529425^\circ + 0.5240207666^\circ d + 0.000013553^\circ D^2 + 0.000000025^\circ D^3$$

Time t or interval $(t-t_0)$, where t_0 is the fundamental epoch 1900, January 0.5 E. T. or Julian Date J. D. 2415020.0, is the fundamental variable and is measured in Julian centuries of 36525 ephemeris days, counted since the fundamental epoch.

However, for convenience the submultiples D and d are used:

$$D = 3.6525 t \text{ (in units of 10000 ephemeris days)}$$

$$d = 10000 D = 36525 t \text{ (in ephemeris days)}$$

- 2) Referred to (fixed) mean equinox and ecliptic of 1950.0 (Sturms, 1970)

$$a = 1.5236915 \text{ AU}$$

$$e = 0.09335891275 + 0.000091987 t - 0.000000077 t^2$$

$$i = 1.85000^\circ - 0.00821^\circ t - 0.00002^\circ t^2$$

$$\Omega = 49.17193^\circ - 0.029470^\circ t - 0.00065^\circ t^2$$

$$\omega = 285.96668^\circ + 0.73907^\circ t + 0.00047^\circ t^2$$

$$M = 169.458720^\circ + 0.5240207716^\circ d + 0.0001825972^\circ t^2 + 0.0000011944^\circ t^3$$

Time t , in this set of equations, is counted from the fundamental epoch 1950, January 1.0 E. T. or Julian Date 2433282.5, and is measured in Julian centuries. It is important to note that this epoch is not exactly the same instant as that of the reference coordinate system epoch 1950.0, which corresponds to Julian Date 2433282.423357. The reason for this small shift is to be able to express the Julian Date in a round number count from the time reference epoch.

Orbital Constants and Derived Tabulated Data

Period of Revolution

The Martian year (687 days) is somewhat less (by 43 days) than two terrestrial years, while the mean interval of 780 days between successive oppositions (mean synodic period) is the longest of all major planets.

The mean daily motion of Mars is slower than that of Earth by 0.461576 degree per day.

$$\begin{aligned} P \quad \text{Period of revolution (sidereal)} &= 686.9804 \text{ mean solar days} \\ &= 1.88089 \text{ tropical years} \end{aligned}$$

n Mean daily motion, $n = 360^\circ/P$ (sidereal) = 0.524033 degree per day

S Mean synodic period* (Earth/Mars) = 779.94 mean solar days

Daily motion. The daily motion (degrees/day) is given for every 4th day of the current and preceding years by the American Ephemeris and Nautical Almanac.

Orbital velocity

	<u>km sec⁻¹</u>	<u>mi sec⁻¹</u>
Mean	24.1	15.0
Perihelion	26.4	16.4
Aphelion	22.0	13.6

The orbital velocity may be calculated from the heliocentric distance (radius vector) r , the semi-major axis a , and the masses of planet m and Sun M by the formula:

$$v \text{ (in AU per day)} = k \sqrt{(M + m) \left(\frac{2}{r} - \frac{1}{a} \right)} \quad \text{Units: } \begin{array}{l} r \text{ and } a \text{ in AU} \\ m \text{ relative to Sun } M = 1. \end{array}$$

where k is the Gaussian gravitational constant ($k = 0.01720209895$)

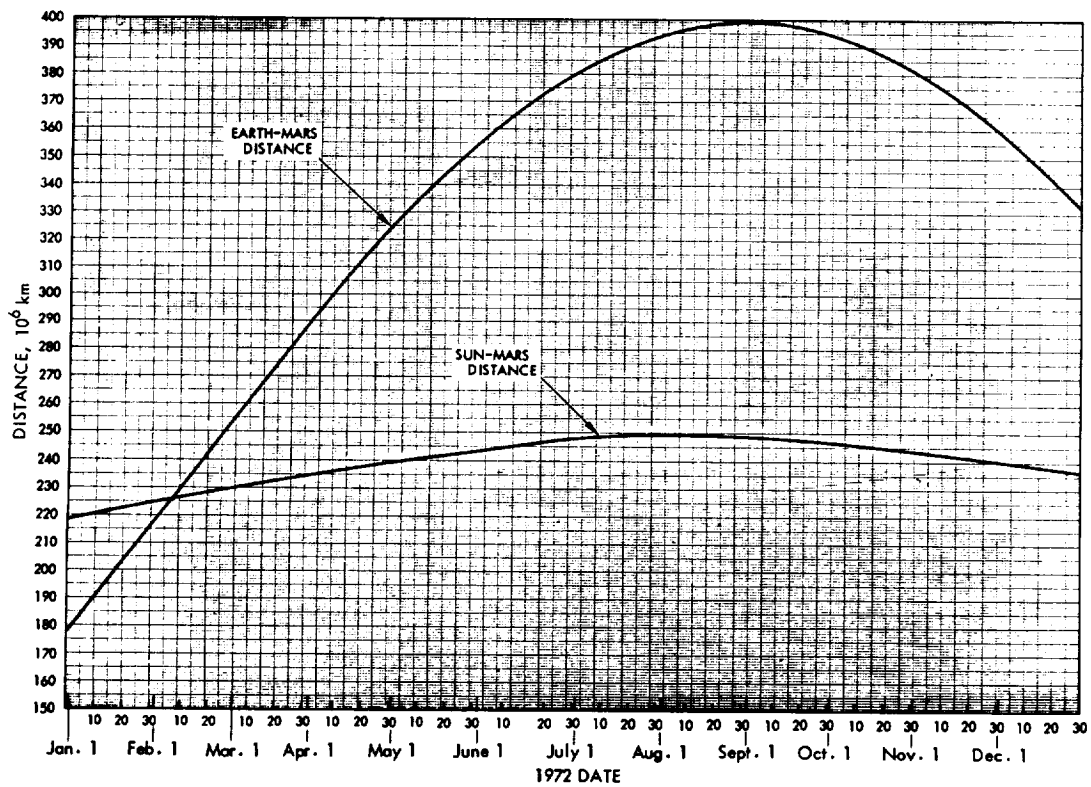
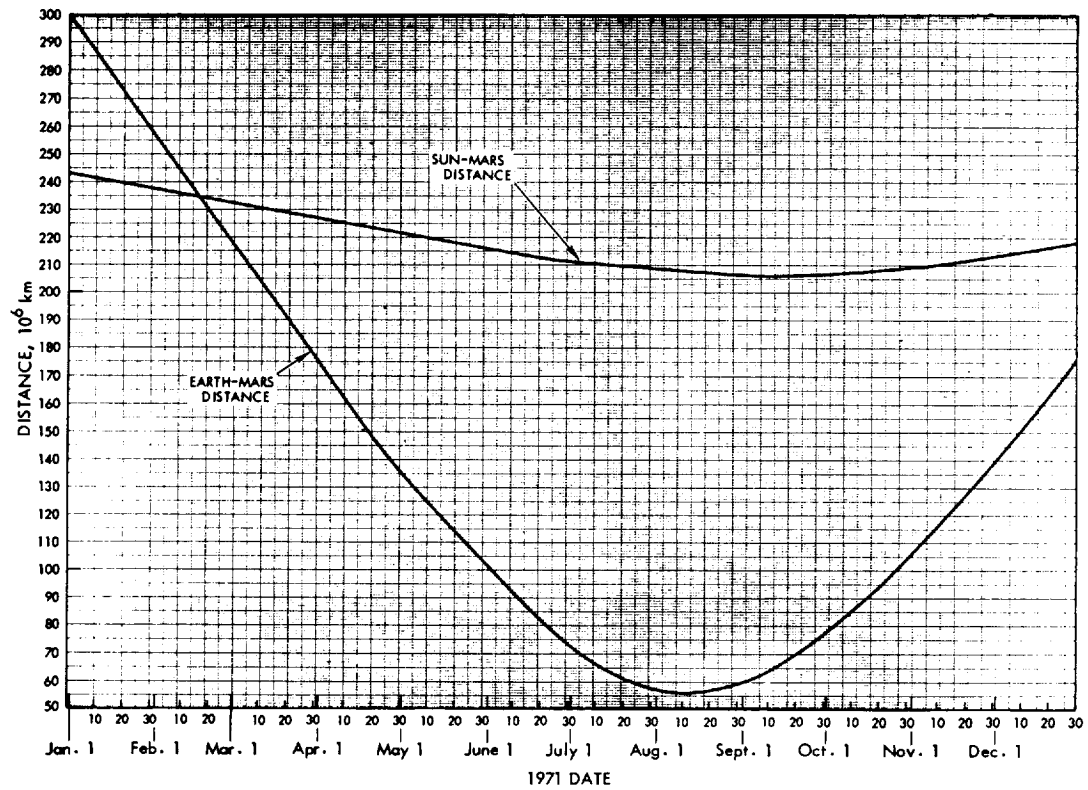
<u>Distance from Sun</u> (Fig. 3)	<u>AU</u>	<u>km</u>	<u>mi</u>
Mean (semi-major axis)	1.5236(91)	227,800,000	141,500,000
Perihelion	1.3815	206,500,000	128,300,000
Aphelion	1.6660	249,100,000	154,800,000

(American Ephemeris
and Nautical Almanac)

The heliocentric distance (radius vector) is given for every 4th day of the current and preceding years by the annual volumes of the American Ephemeris and Nautical Almanac, and for every 10th day for years 1800 to 1980 by the Planetary Coordinates tables; and for 1973 to 2000 by the tables and graphs issued by Souders (1970).

*The synodic period S is derived from the sidereal periods P_m of Mars and P_e of Earth ($P_e = 365.25636$ d) by the relation used for superior planets:

$$\frac{1}{S} = \frac{1}{P_e} - \frac{1}{P_m}$$



NOTE: Similar figures were issued by Souders (1970) for the years 1973-2000.

Fig. 3. Distances of Mars from Sun and Earth.

<u>Distance from Earth</u> (Fig. 3)	<u>AU</u>	<u>km</u>	<u>mi</u>
Mean opposition	0.5236	78,350,000	48,695,000
Minimum distance	0.3728	55,810,000	34,670,000
Maximum distance	2.6657	398,900,000	247,900,000

(American Ephemeris
and Nautical Almanac)

The geocentric distance (Earth-Mars separation) is given for every day of the current and preceding years by the American Ephemeris and Nautical Almanac, and for every 10th day of years 1973 to 2000 by the tables and graphs issued by Souders (1970).

Opposition dates and minimum distances (at closest approach) are listed in Tables 1 and 2 for years 1937 to 1980. Figure 4 illustrates orbital occurrences of many oppositions from 1877 to 1988. Figure 5 compares angular sizes of the Martian disk as seen from Earth through a complete 15.8-year (average) cycle of successive oppositions. Superior conjunction dates and maximum distances are listed in Table 3 for years 1960 to 2000, as established from Souders' (1970) tables using graphic interpolation and from the American Ephemeris and Nautical Almanac.

Rotational Elements

The solid surface of Mars is visible most of the time, which permitted early observers to quite accurately determine its rotation period. The current rotation period data is accurate to within 0.02 second. The usual method of determination consists in timing transits of conspicuous surface features (e.g., Meridiani Sinus) across the central meridian of Mars. It is also possible to measure the areographic longitude of a surface feature on a photograph taken at a precise time. This sometimes has been applied to old drawings, although the resultant accuracy is questionable. It was done, however, by Wislicenus (1886), and Bakhuyzen (1897), and provided good results, $24^{\text{h}}37^{\text{m}}22^{\text{s}}.66$, when compared to the modern value, +22.67 seconds, derived by Ashbrook (1953), utilizing only transit material (1877-1952 period).

The present orientation of Mars' axis of rotation in the celestial sphere – some 10° from the star Deneb – is known with lesser accuracy than the rotation period, probably to within 0.1° (according to de Vaucouleurs, 1971, private communication). The inclination of Mars' equator to its orbit, or the Martian "obliquity," is very nearly 25° . See Figure 6.

The precession rate of the Mars' axis, or of its equinoxes, is not too accurately known. Determinations by Struve (1898) – 7.07 arc seconds/year, and by Lowell (1914) – 7.08 arc seconds/year, were questioned by Fish (1964), who proposed 7.34 arc seconds/year (using de Vaucouleurs' inclination value). The precession rate is still in question, but Struve's value is most commonly utilized. The corresponding precessional period is about 183,300 years.

Table 1. Opposition dates of Mars. (Data from Slipher, 1962; American Ephemeris and Nautical Almanac, 1937-1972; Miner, 1967)

Date of opposition	Interval from previous date, days	Distance from Earth ^a	
		Million miles	Million kilometers
1937 May 19		47.3	76.1
1939 Jul 23	795	36.1	58.0
1941 Oct 10	810	38.2	61.4
1943 Dec 5	786	50.1	80.7
1946 Jan 14	771	60.4	95.6
1948 Feb 17	764	63.0	101.4
1950 Mar 23	765	60.4	97.2
1952 May 1	770	51.9	83.5
1954 Jun 24	784	39.8	64.1
1956 Sep 11	806	35.2	56.6
1958 Nov 17	800	45.4	73.0
1960 Dec 30	775	56.3	90.6
1963 Feb 4	776	62.2	100.1
1965 Mar 9	763	62.0	99.8
1967 Apr 15	767	55.8	89.8
1969 May 31	777	44.5	71.7
1971 Aug 10	781	34.9	56.2
1973 Oct 25	807	40.4	65.0
1975 Dec 15	791	52.4	84.3
1978 Jan 22	771	60.8	97.8
1980 Feb 25	764	63.2	101.7
^a At closest approach, which may be as much as 10 days before or after opposition.			

Table 2. Exceptionally close Mars approaches.

Date of opposition	Interval from previous date, years	Distance from Earth ^a	
		Million miles	Million kilometers
1877 Sep 5		34.8	56.0
1892 Aug 26	15.0	34.5	55.5
1909 Sep 18	17.1	36.2	58.3
1924 Aug 22	14.9	34.5	55.5
1939 Jul 23	14.9	36.1	58.0
1956 Sep 11	17.2	35.2	56.6
1971 Aug 10	14.9	34.9	56.2
1988 Sep 28	17.2	36.3	58.4
^a At closest approach, which may be as much as 10 days before or after opposition.			

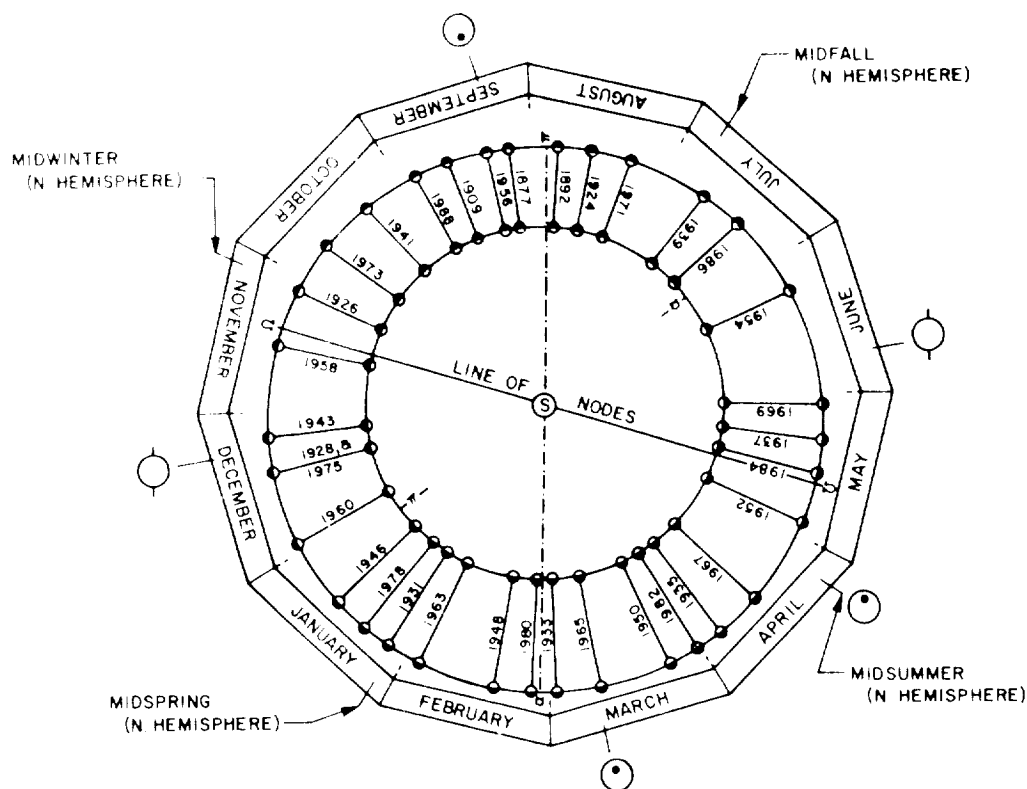


Fig. 4. Oppositions of Mars from 1877 to 1988. Surrounding calendar indicates time of occurrence. Broken line is major axis of Mars orbit connecting aphelion and perihelion. Aphelion and perihelion of Earth are indicated on Earth orbit.
(After Ley, Von Braun, and Bonestell, 1960)

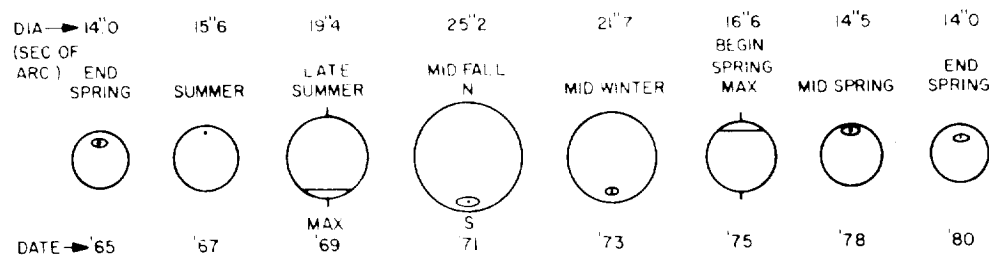


Fig. 5. Apparent angular sizes of disk of Mars at oppositions from 1965 to 1980. Seasons indicated are for northern hemisphere. North and south poles and approximate extent of polar caps are indicated. (Miner, de Wys, 1967)

Table 3. Superior conjunctions, Earth-Mars, 1960-2000

Year	Superior Conjunction			Furthest Distance		
	Date	Conjunction Distance		Date	Furthest Distance	
		Million kilometers*	Million miles		Million kilometers*	Million miles
1961	Dec. 14	367	228	Nov. 7	371	231
1964	Feb. 17	355	221	Feb. 20	355	221
1966	Apr. 29	367	228	Jun. 13	373	232
1968	Jun. 21	387	240	Jul. 15	389	242
1970	Aug. 2	398	247	Aug. 9	399	248
1972	Sep. 7	400	249	Sep. 1	400	249
1974	Oct. 16	391	243	Sep. 23	394	245
1976	Nov. 26	374	232	Oct. 24	378	235
1979	Jan. 21	358	222	Dec. 13 (1978)	359	223
1981	Apr. 2	359	223	May 21	364	226
1983	Jun. 4	380	236	Jul. 4	384	239
1985	Jul. 18	395	245	Aug. 1	396	246
1987	Aug. 27	400	249	Aug. 28	400	249
1989	Oct. 1	395	245	Sep. 15	397	247
1991	Nov. 10	381	237	Oct. 13	385	239
1993	Dec. 27	363	226	Nov. 19	367	228
1996	Mar. 6	355	221	Apr. 17	357	222
1998	May 13	372	231	Jun. 21	377	234
2000	Jul. 2	391	243	Jul. 20	392	244

*Calculations using the value adopted by the I. A. U. in 1968 for
 1 A. U. = 149600×10^6 m.

Position of Mean North Pole of Mars (See Fig. 6)

The following formulae for right ascension (α_0) and declination (δ_0) of the Mars North Pole, referenced to the mean (Earth) equator and ecliptic, include the effects of known precession rates for Mars and Earth north poles, but not the effects of nutation (which may be neglected in view of the present accuracy of the formulae).

1) With respect to the (moving) mean equator and ecliptic of date:

$$\alpha_0 = 316.55^\circ + 0.006751^\circ(t - 1905.0) \quad \begin{array}{l} \text{(de Vaucouleurs, 1964)} \\ \text{(A. E., 1968; 1971)} \end{array}$$

$$\delta_0 = 52.85^\circ + 0.003480^\circ(t - 1905.0) \quad \text{corrected}$$

at start of year t .

2) With respect to the (fixed) mean equator and ecliptic of 1950.0:

$$\alpha_{50} = 316.8538^\circ - 0.0996^\circ t \quad \text{(Sturms, 1970)}$$

$$\delta_{50} = 53.0066^\circ - 0.0566^\circ t$$

where time interval t is counted from the 1950, January 1.0 E. T., time reference epoch in Julian centuries.

Formulae 2) were derived from formulae 1) by Sturms (1970) using the appropriate coordinate transformations explained in his document, but only include the Martian precession.

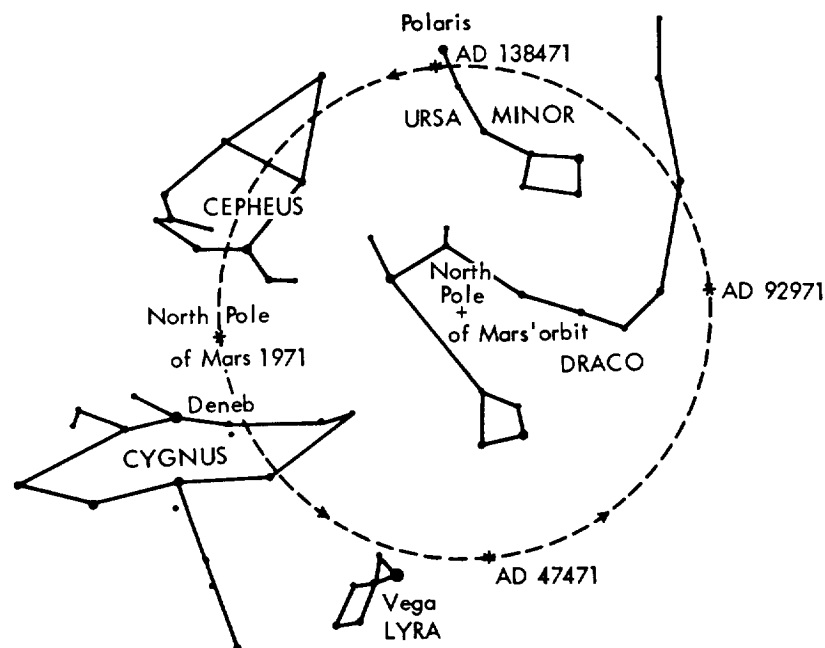


Fig. 6. Precession of the Martian North Pole.

3) Rate of precession of Mars North Pole used in these formulae:

$$\mu = 7.07 \text{ arc seconds per tropical year} \quad (\text{Struve, 1895})$$

This precessional rate appears to be in need of revision, which would immediately affect the rate coefficients in the above formulae.

Derived quantities (from formulae 2) above:1) Martian "obliquity" (inclination of Mars equator to orbit):

$$I = 24.76883^\circ + 0.01220^\circ t + 0.00006^\circ t^2 \quad (\text{Sturms, 1970})$$

where time interval t is counted from the 1950, January 1.0 E.T. time reference epoch (as previously) in Julian centuries.

2) Angle along Mars equator, measured from ascending node on the mean 1950.0 Earth equator to the Mars autumnal equinox: this angle is a quantity useful in making coordinate transformations.

$$\Delta_{50} = 43.34526^\circ - 0.09181^\circ t - 0.00010^\circ t^2 \quad (\text{Sturms, 1970})$$

where t is measured as in 1) in Julian centuries.

Period of Rotation of Mars

The rotational period of Mars has been known with great accuracy for sometime because of the visibility of the surface itself. Two periods may be distinguished:

1) Sidereal period of rotation, which is referred to the (moving) Martian vernal equinox: (This is the period usually quoted.)

$$P = 24^h 37^m 22.6689 \pm 0.0026 \text{ (m. e.) E. T.} \quad (\text{Ashbrook, 1953})$$

Note: The period in mean solar time is 0.0010 seconds shorter over the period of transit observations, 1879-1952, considered by Ashbrook in deriving his value. For more information, see de Vaucouleurs (1964).

2) True or actual period of rotation; i. e., relative to a fixed direction, eliminating the precession of the Martian equinox)

$$P = 24^h 37^m 22.6701 \pm 0.0026 \text{ (m. e.) E. T.} \quad (\text{Ashbrook, 1953 and de Vaucouleurs, 1964})$$

It is 0.0012 seconds longer than the so-called "sidereal" period (assuming $\mu = 7.07$ arc sec per year).

Derived Quantities1) Sidereal rate of rotation, or daily angular rotation:

$$R = \frac{360^\circ}{P} = 350.891962 \text{ degrees per terrestrial day}$$

This rotation rate was adopted in 1960 by the American Ephemeris Office for computation of its Ephemeris for Physical Observations of Mars, specifically for the "longitude of the central meridian."

- 2) The longitude of the central meridian (L. C. M. or ω) at any time t in the Martian longitude system (see below). L. C. M. is the Martian hour angle of the Earth measured from the zero meridian. It is determined by the adopted longitude of the central meridian $\omega_0(t_0)$ at a chosen epoch t_0 and the rotation rate R , as well as the orbital positions of Earth and Mars, according to the formula with light-time correction (see Fig. 7):

$$(L.C.M. \equiv) \omega = V_0 + R (t - t_0) - k\Delta - |A_E|$$

where

Values Adopted by
American Ephemeris, 1971:

V_0 = value of V (defined below) at chosen epoch t_0

$V_0 = 149.475$ deg

k = value of light-time per AU

$k = 0.00577560$ day AU⁻¹
(= 499.012 sec AU⁻¹)

Δ = geocentric distance of Mars in AU

A_E = areocentric right ascension of Earth

R = sidereal rate of rotation of Mars

$R = 350.891962$ deg day⁻¹

$(t - t_0)$ = time in Julian days since epoch t_0

$t_0 = \text{J. D. } 2418322.0$
(i.e., 1909.04 epoch)

Martian Longitude System (Adopted by American Ephemeris, 1909)

Areographic longitudes are measured from 0° to 360° opposite to rotation direction (that is, clockwise as viewed from Mars North Pole) along the equator of Mars corresponding to the adopted position of the North Pole (see above) and an adopted value (in 1909) for the longitude of the central meridian, as follows:
 $\omega_0 = 344.41^\circ$ at chosen epoch t_0 of 1909.04 (January 15.5 U. T.), or
 $t_0 = \text{J. D. } 2418322.0$.

The zero meridian, or origin of longitudes, with this 1909 convention, then falls at a point on Mars' surface that is about 3 degrees west of the old origin of longitudes (as used by Schiaparelli, Marth, etc.), which was the apex of the wedge dividing Meridiani Sinus (and called Fastigium Aryn).

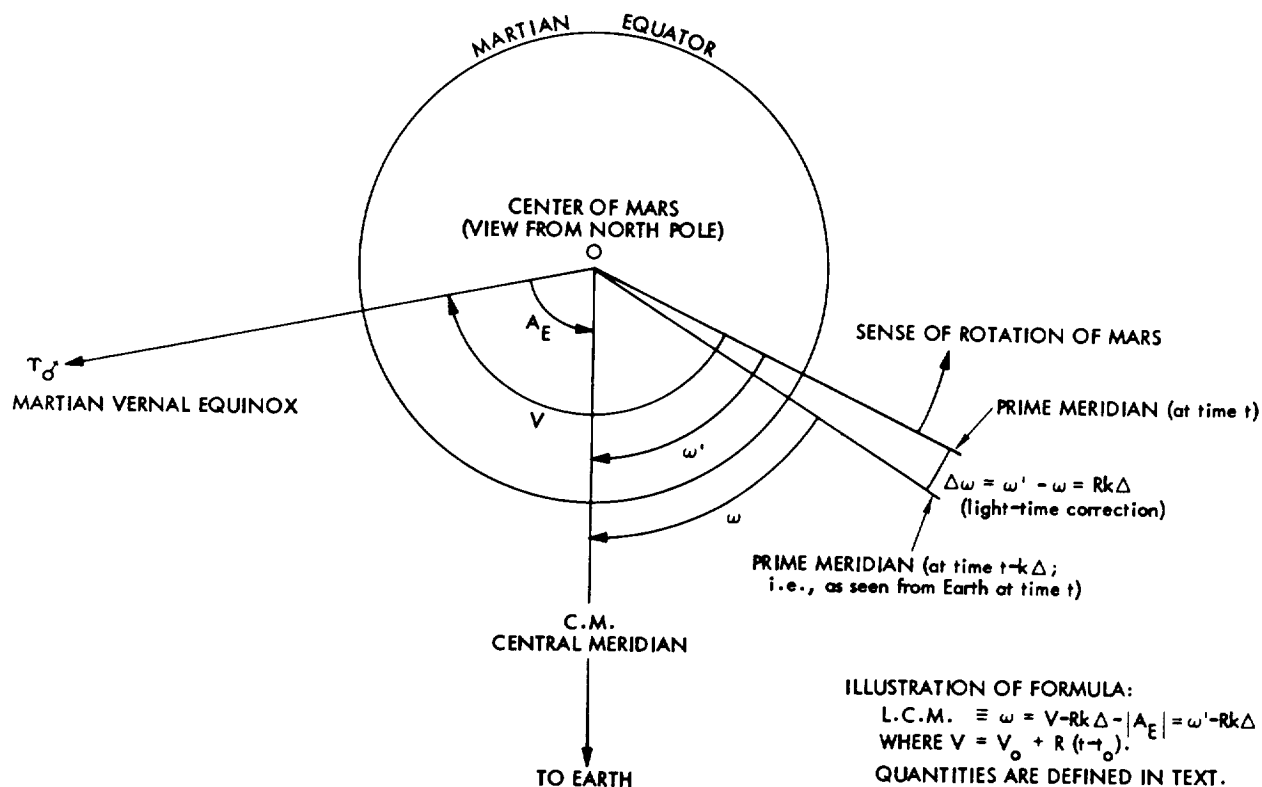


Fig. 7. Longitude of central meridian

- 3) The Martian hour angle of the Martian vernal equinox, measured from the zero meridian of the Martian longitude system. It is given either by:

$$V = 149.475^\circ + 350.891962^\circ (\text{J. D.} - 2418322.0) \quad (\text{Melbourne et al. 1968})$$

where time is counted in days since reference epoch 1904 January 15.5 U. T.; or by:

$$V = 148.672501^\circ + 350.891962^\circ (\text{J. E. D.} - 2433282.5) (\text{Sturms, 1970})$$

where time is counted in (ephemeris) days since reference epoch 1950, January 1.0 E. T.

Physical Data Summary

Physical characteristics (constants) of Mars are identified in Table 4, which presents the best available values to date, both in absolutes and relative to Earth.

Table 4. Mars physical data summary.

Characteristic parameter	Relative (Earth=1)	Absolute value	Source
Flattening:			
Geometrical (Mariner Occultation Expts)	1.70	0.0057 $\pm$ 0.0012	Kliore(1971)
Dynamical (satellites orbits)		0.00525	Cain (1967 a)
Optical (telescopic)		0.012	
External gravitational potential:			
Zonal harmonic coefficient J_2	1.73	0.00187 $\pm$ 0.00007	Null(1971)
Radius:			
Equatorial (Mariner Occultation Expts)	0.5320	3393 $\pm$ 2 km	Kliore(1971)
At 88°N latitude (Mariner Occultation Expts)		3370 $\pm$ 5 km	Kliore(1971)
Polar* (calculated from equatorial radius and dynamical flattening)	0.5310	3375 km	
Surface area of:			
Ellipsoid (calculated from radii)	0.283	1.4418 $\times 10^8$ km ²	
Volume:			
Ellipsoid (calculated from radii)	0.150	1.6282 $\times 10^{11}$ km ³	
*No polar radius measurement is available yet from occultation experiments.			

Table 4. Mars physical data summary (continued).

Characteristic parameter	Relative (Earth=1)	Absolute value	Source
Areocentric gravitational constant $GM_{\oplus}$ (Gravitational constant x mass) (Mariner 4)	0.1074	$42828.32 \pm 0.13 \text{ km}^3 \text{ sec}^{-2}$	Anderson, Efron, and Wong(1970)
Mass $M_{\oplus}$ (derived using** $G = 6.6732 \times 10^{-23} \text{ km}^3 \text{ g}^{-1} \text{ sec}^{-2}$)	0.1074	$6.418 \times 10^{26} \text{ g}$	
Reciprocal mass (relative to Sun = 1) $M_{\odot}/M_{\oplus}$	(1/0.1074)	3098714 ± 9	Null(1971)
Density: Mean (calculated from mass and volume)	0.715	3.945 g cm^{-3}	
Surface gravity: Equatorial (calculated from Clairaut's equation and data of this section)	0.379	371 cm sec^{-2}	
Velocity of escape: Equatorial (calculated)	0.449	$5.024 \text{ km sec}^{-1}$	
**Value of G determined by Heyl (1942) and recommended by Mulholland et al. (1968).			

Seasons of Mars

Mars has seasons comparable to those of Earth because of the nearly equal tilt of its axis to its orbital plane. However, the seasons, in the average, are about twice as long, which correspond to the greater length of the Martian year. Furthermore, they are distinctly unequal in duration, as a result of the appreciable eccentricity of the Martian orbit. Table 5 gives the durations of these seasons in terrestrial and Martian day units, and also the areocentric longitudes of the Sun at the two equinoctial and two solstitial points. Figure 8 compares the occurrence of terrestrial and Martian seasons and shows that they do not occur at the same heliocentric longitudes. This is because of the different celestial orientation of the two rotational axes. Mars' axis is about 37° away from that of Earth. It is actually 85° in heliocentric longitude ahead of Earth's in its (also retrograde) precessional motion around the pole of its orbit. The orbit pole of Mars is very close to the pole of the ecliptic (only 1.85° away, as orbital inclination shows).

In the course of time, the seasons of Mars change very slowly both in celestial and orbital positions because of the precessions of the node (or line of equinoxes) and of the perihelion (or line of apsides). The effects (such as change in duration of the seasons) are more marked than in the case of the Earth because of the orbit's fair eccentricity. The Martian seasons go through an effective precessional cycle of about 52,000 years period, which is determined by the combination of the period of regression of the node ($\sim 183,000$ years) and of the period of advance of the perihelion ($\sim 72,000$ years, according to Brouwer and Clemence, 1961).

The areocentric longitude of the Sun, L_S — which indicates seasonal date on Mars — is found tabulated for every second day through Mars apparition periods in the American Ephemeris and Nautical Almanac annual volumes (under Mars-Ephemeris for Physical Observations). The relationship of L_S to the heliocentric orbital longitude of Mars, commonly denoted by η , is at present approximately: $L_S \simeq \eta - 85^\circ$ (constant varying very slowly with precession).

Table 5. Earth-Mars seasonal durations.

Areocentric longitude of the Sun L_S	Season		Duration of the seasons on		
	Northern Hemisphere	Southern Hemisphere	Mars		Earth
			Martian days	Terrestrial days	Terrestrial days
0 - 90°	Spring	Autumn	194	199	92.9
90 - 180°	Summer	Winter	178	183	93.6
180 - 270°	Autumn	Spring	143	147	89.7
270 - 360° or 0°	Winter	Summer	154	158	89.1
			669	687	365.3

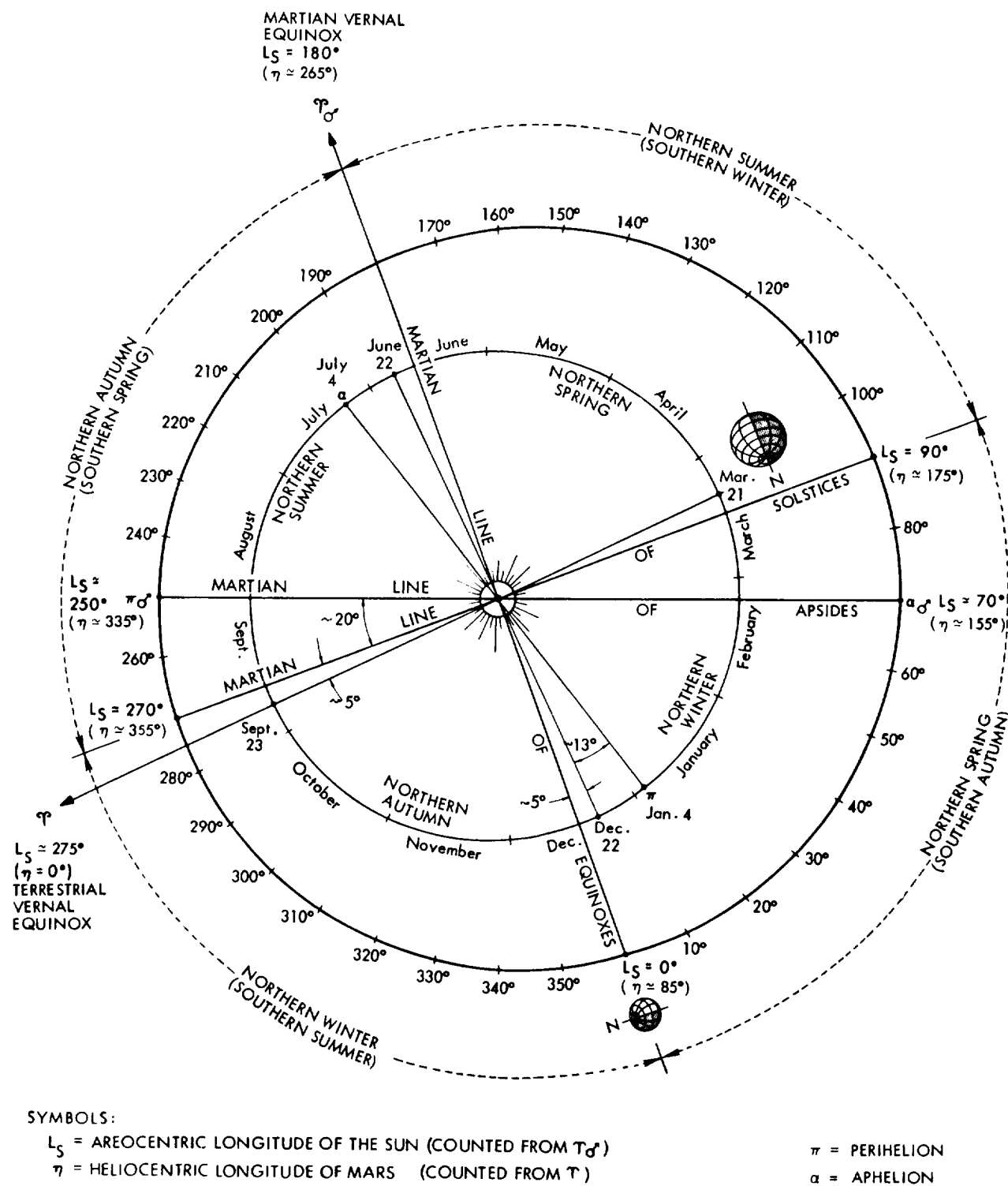


Figure 8. Comparison of the Martian seasons and the terrestrial seasons (in 1971).

Earth-Mars Calendar (See Appendix A)

A Martian calendar is desirable to establish an equivalence of Earth and Mars dates, and to simplify the presentation and interpretation of secular and seasonal changes on Mars. [Note by C. Michaux, 1972 : The accompanying calendar (Table A-1) was developed by R. Norton in 1967 and was based on the position of the Mars North Pole in use then (A.E. 1905-1968). A revision is to be issued later.]

Equivalences

The basic units of time for a Mars calendar are the Mars tropical year and the Mars mean solar day. The variability of the length of Martian seasons resulting from the eccentricity of the orbit, limits the usefulness of a seasonal calendar. However, seasons, referred to the Northern Hemisphere, have been included in the calendar as rough approximations, beginning on the days listed below; no attempt has been made to define "months."

- 1) One mean Mars day = 1.02749133 mean Earth solar days.
(= $24^h 39^m 35^s.2509$).
- 2) One Mars tropical year = 668.592159 Mars solar days.
- 3) Mars spring begins on day 167.1.
- 4) Mars summer begins on day 361.3.
- 5) Mars fall begins on day 538.1.
- 6) Mars winter begins on day 11.3.

Basis of Zero Points

The year 1000 has been adopted as the year of the Mariner IV flyby. The start of this year has been defined such that the time of year was approximately 0.25 when Mars passed its vernal equinox prior to the Mariner IV flyby in July of 1965. This equinox occurred on September 12, 1964, Earth time and has therefore been designated as day number 167 of the Martian year 1000.

The start of each day on Mars is defined to be at midnight at 0° longitude; i. e., each day starts when the subsolar longitude is 180° .

Mars Leap Years

A Mars leap year is defined as follows:

- 1) If year is odd, it is a leap year (669 Mars solar days).
- 2) If year is even, it is not a leap year, except
 - a) if year is divisible by 10, it is a leap year, except
 - b) if year is divisible by 100 it is not a leap year, except
 - c) if year is divisible by 500 it is a leap year.

At the conclusion of a Martian 500-year cycle, the cumulative error between the calendar date and the astronomical date, based on the tropical year, amounts to 0.08 Mars solar day (about two hours). This accuracy is slightly better than that of the present Earth calendar.

In the Earth-Mars calendar, the column labeled 'Consecutive Mars day' lists a day number for Mars, similar to the Julian day number for Earth. Consecutive Mars day number 1 was the first day of the Martian year 0 (which was a leap year). The calendar also contains a column of heliocentric ecliptic longitude equivalents for each day. Earth-Mars data for 1963 through 1983 are presented at this time.

An additional column has been included in Table A-1 to give opposition dates and distances, spacecraft events, and other information which may be of interest. The calendars also can be used to correlate Martian seasons with past observations.

Earth dates are for 0^h GMT; Mars dates show day of year and fraction of day elapsed at 0° longitude on Mars.

1.2 SATELLITES – ORBITAL AND PHYSICAL DATA

Orbital Elements

The two Martian satellites, Phobos and Deimos, discovered in 1877 by A. Hall, are very small and revolve quite close to the surface of Mars. Phobos, in fact, revolves faster than Mars rotates, and is the only natural satellite in the solar system known to behave in this manner. The orbits of the two satellites are nearly circular and lie very close to the equatorial plane of Mars. As demonstrated in celestial mechanics, the perturbations principally due to the oblateness of Mars, but also to the Sun, cause each orbit to precess on a fixed "Laplacian," plane passing through the intersection of the equatorial and orbital planes of Mars, and lying between them though closer to the Mars equatorial plane. The relation between these planes is illustrated in Fig. 9. The most reliable orbital characteristics data, Wilkins (1965), are presented in Table 6. The orbital elements of each satellite are given, using its fixed (Laplacian) plane as a reference plane, which itself is referred to the standard Earth equinox and equator plane of 1950.0 (conversion by Cain, 1967b). The original notation of Wilkins is explained in Table 7 and illustrated in Fig. 10. According to Wilkins' analysis of all existing data, the secular acceleration in longitude of Phobos, once claimed by Sharpless (1945), is unsubstantiated. Related orbital data is presented in Table 8.

Physical Data

Physical data for the two Martian satellites are rather inadequate as shown in Table 9. Recently, the size, shape and albedo of Phobos have been estimated from several Mariner 7 TV pictures. Phobos is approximately 20 km across (mean diameter), and elongated in the plane of its orbit, while possessing an extremely dark surface (Smith, 1970).

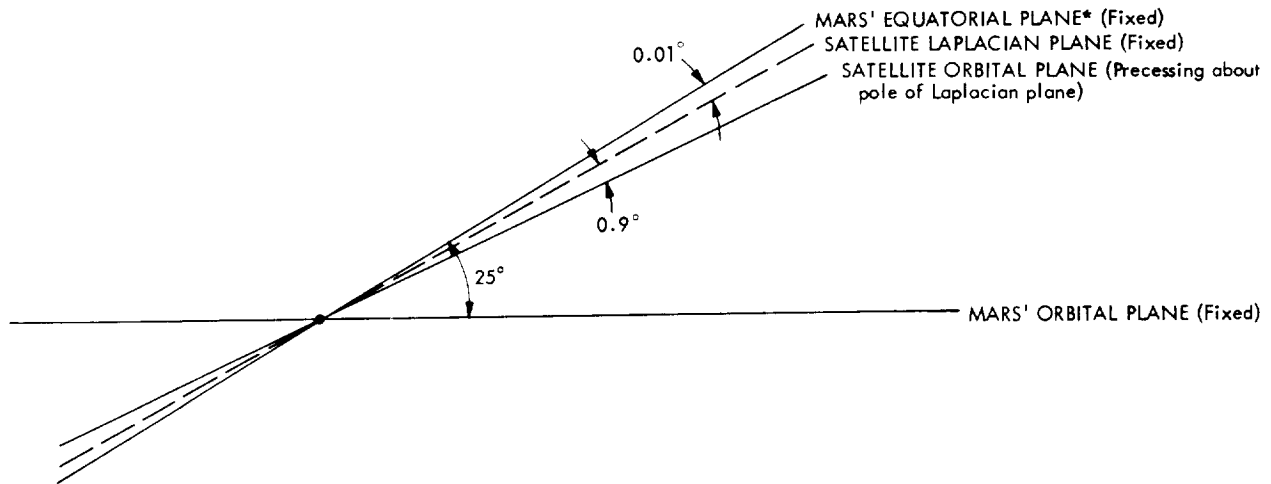
The masses of these minuscule satellites are still unknown, as are their densities.

Table 6. Orbital elements of the Martian satellites. [Least-square solution fitting all optical data, as proposed by Wilkins (1965) and converted to the epoch 1950.0 by Cain (1967b), with minor modification* in A by Cain (1966).]

Elements for equinox of 1950.0 and epoch $t_0 = \text{J. D. 2433282.5}$ (almost exactly 1950.0)	Symbol	Phobos	Deimos
Longitude of node of fixed plane	N_A	46.9 deg	46.40 deg
Inclination of fixed plane to equator	J_A	37.57 deg	36.64 deg
Argument of node of orbital plane at epoch	K_Z	177.28 deg	25.62 deg
Mean daily motion of node of orbital plane	K_R	$-0.438 \text{ deg day}^{-1}$	$-0.0180 \text{ deg day}^{-1}$
Inclination of orbital plane to fixed plane	I	0.90 deg	1.80 deg
Mean longitude at epoch	L_Z	136.21 deg	296.475 deg
Mean daily motion in longitude	L_N	$1128.8443 \text{ deg day}^{-1}$	$285.16192 \text{ deg day}^{-1}$
Longitude of pericenter at epoch	P_Z	76 deg	(236) deg formal, $e = 0$
Mean daily motion of pericenter	P_R	$0.436 \text{ deg day}^{-1}$	(0.016) deg day^{-1} formal, $e = 0$
Apparent semi-major axis at unit distance	A	$12.926 \pm 0.001 \text{ arc sec}$ (9375.0 $\pm 0.6 \text{ km}$)	$32.344 \pm 0.002 \text{ arc sec}$ (23,457.7 $\pm 1.5 \text{ km}$)
Eccentricity of orbit	e	0.018	0.0
*Note: Cain (1966) modified slightly the semi-major axis values A to take into account the latest (Mariner 4) mass value of Mars.			

Table 7. Nomenclature for the system of orbital elements necessary for calculating a Marian satellite's position at anytime t after epoch t_0 .

Orbital element	Definition
N_A	Longitude (TA) of ascending node (A) of fixed (Laplacian) plane of satellite on Earth standard equator (for 1950.0) [as measured along this equator from vernal equinox Υ .]
J_A	Inclination of fixed (Laplacian) plane to Earth standard equator.
K	Longitude (AC) of ascending node (C) of orbital plane of satellite on its fixed (Laplacian) plane, [as measured along this plane from ascending node A]. It is given by linear expression: $K = K_Z + K_R (t - t_0)$, where t_0 is the epoch (J.D. 2433282.5, near 1950.0) and t the current Julian Date; therefore, $(t - t_0)$ in ephemeris days and K_Z and K_R as below:
$\left\{ \begin{array}{l} K_Z \\ K_R \end{array} \right.$	Longitude K at epoch t_0 . Mean rate of regression of ascending node C or of its longitude K (units: deg day ⁻¹). K_R is constant and negative.
I	Inclination of orbital plane of satellite to Laplacian plane. I is constant.
L	Mean longitude (TA + AC + C $\bar{S}$) of satellite ($\bar{S}$), as measured along Earth equator from its vernal equinox Υ to node A, then along Laplacian plane to node C, and finally along satellite orbit to satellite mean position $\bar{S}$. It is given by quadratic expression: $L = L_Z + L_N (t - t_0) + L_M (t - t_0)^2$, where $(t - t_0)$ interval as above, and L_Z , L_N as below:
$\left\{ \begin{array}{l} L_Z \\ L_N \\ L_M \end{array} \right.$	Longitude L at epoch t_0 . Mean rate of advance (mean daily motion) of satellite $\bar{S}$ around its orbit. (L_N is considered constant at least over many years.) <u>Secular</u> acceleration in longitude L of satellite. (L_M is, at most, extremely small; in fact, according to Wilkins' analysis, $L_M = 0$.)
P	Longitude (TA + AC + CP) of pericenter (P) of satellite orbit, as measured like L . It is given by linear expression: $P = P_Z + P_R (t - t_0)$, where $(t - t_0)$ as defined previously, and P_Z , P_R as defined below:
$\left\{ \begin{array}{l} P_Z \\ P_R \end{array} \right.$	Longitude P at epoch t_0 . Mean rate of advance of pericenter P around the orbit, or of its longitude P (units: deg day ⁻¹). P_R is constant and positive.
A	Semi-major axis of satellite orbit at unit distance or 1 AU. (Units used: seconds of arc.)
e	Eccentricity of satellite orbit.



*AS DEFINED BY THE GRAVITATIONAL POTENTIAL OF MARS.

Fig. 9. The Laplacian plane of a Martian satellite (values of angles are for Phobos).

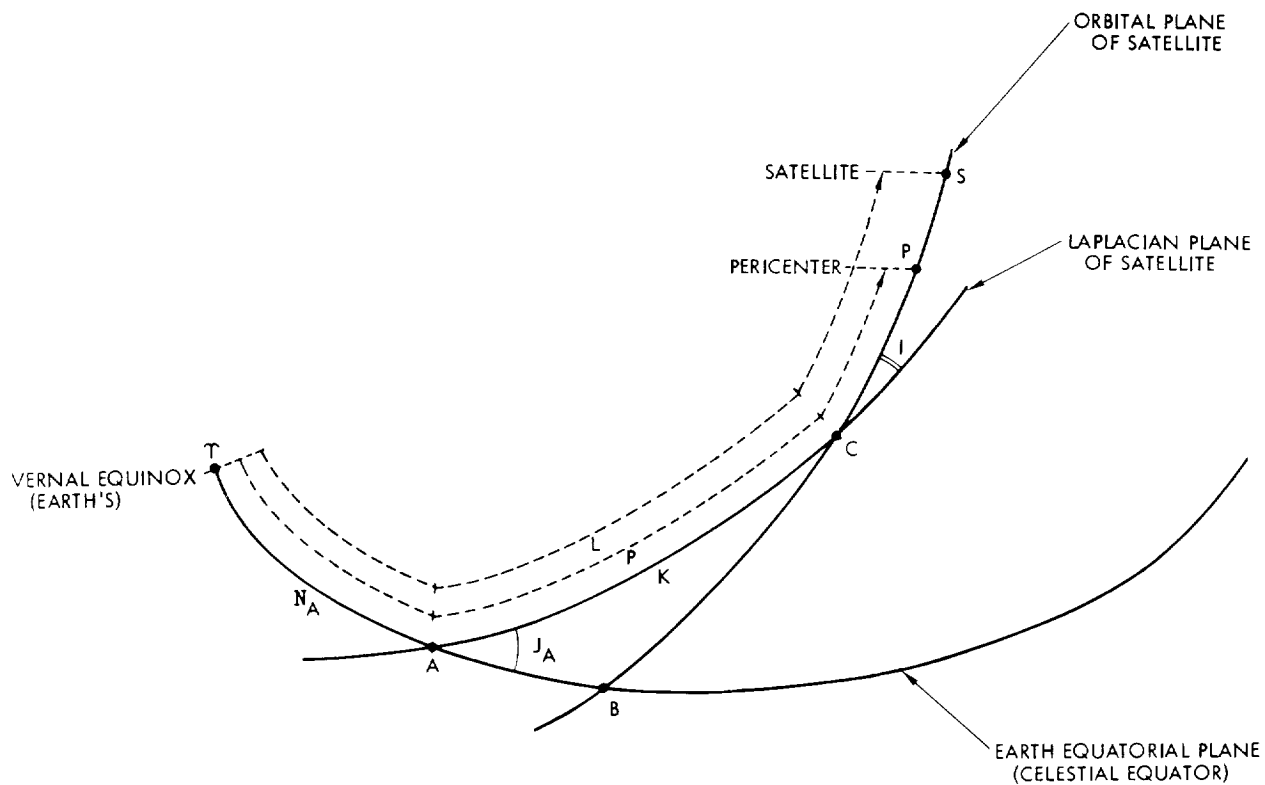


Fig. 10. Illustration of the notation used by Wilkins (1965) and Cain (1967) in deriving the orbital elements of the Martian satellites.

Table 8. Satellite orbital and related data.

Characteristic	Phobos	Deimos
Distance from center of Mars:		
Mars radius = 1 ($R_{eq} = 3393$ km)	2.763	6.913
Kilometers	9375	23457
Miles	5825	14575
Distance above surface of Mars:		
Kilometers	5982	20064
Miles	3717	12467
Period of revolution:		
Sidereal ($P = \frac{360^\circ}{n}$ (or L_N))	$7^h 39^m 13^s.85$ or 0.31891^d	$1^d 6^h 17^m 54^s.87$ or 1.26244^d
Synodic	0.319^d	1.265^d
Orbital eccentricity:	$0.018 (\pm 0.001)$	$0.0 (\pm 0.0003)$
Rate of regression of nodes:	$-159.976^\circ \text{ yr}^{-1}$ or $-0.438^\circ \text{ day}^{-1}$	$-6.574^\circ \text{ yr}^{-1}$ or $-0.0180^\circ \text{ day}^{-1}$ (Wilkins, 1965)

Table 9. Physical data of Martian satellites.

Characteristic	Phobos	Deimos
Diameters:	18 × 22 (elongated in orbital plane) (Smith, 1970; from Mariner 7 TV pictures)	10 km Estimated
Geometric albedo: (average visual)	0.065 (Smith, 1970; from Mariner 7 TV pictures)	
Apparent visual magnitude from Earth: (at mean opposition distance)	11.6 (Harris, 1961)	12.8 (Harris, 1961)
Color: (magnitude B-V)	0.6 (greenish) (Harris, 1961)	0.6 (greenish) (Harris, 1961)

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APPENDIX A

EARTH-MARS CALENDAR

The attached Earth-Mars Calendar, Table A-1, correlates the Earth-Mars periods in three categories of time: Earth calendar dates, Julian Dates, and Consecutive Mars day(s).

The Consecutive Mars day entries are similar to the Julian day number for Earth.

Table A-1. Earth-Mars Calendar

EARTH			MARS				NOTES
J.D. Julian day	Northern hemisphere season and date	Year	Year	Northern hemisphere season and year day	Consecutive Mars day	Heliocentric ecliptic longitude, deg	
2438030.5	WINTER Jan 1	1963	999 (leap year)	SPRING 232.670	668155.66	119.52	FEB 4. APHELIC OPPOSITION Earth-Mars distance at closest approach, 62.2 million mi (100.1 million km). Earth days until next opposition: 763.
2438040.5	Jan 11			242.403	668165.40	124.04	
2438050.5	Jan 21			252.135	668175.13	128.52	
2438060.5	Jan 31			261.868	668184.87	132.97	
2438070.5	Feb 10			271.600	668194.59	137.39	
2438080.5	Feb 20			281.333	668204.33	141.79	
2438090.5	Mar 2			291.065	668214.06	146.18	
2438100.5	Mar 12			300.798	668223.80	150.55	
2438110.5	SPRING Mar 22			310.530	668233.52	154.92	
2438120.5	Apr 1			320.262	668243.26	159.29	
2438130.5	Apr 11			329.995	668252.99	163.66	
2438140.5	Apr 21			339.727	668262.73	168.04	
2438150.5	May 1			349.460	668272.45	172.44	OCT 3-DEC 31. Mars not clearly visible from Earth for physical observations.
2438160.5	May 11			359.192	668282.19	176.85	
2438170.5	May 21			SUMMER 368.925	668291.92	181.30	
2438180.5	May 31			378.657	668301.66	185.77	
2438190.5	Jun 10			388.390	668311.38	190.27	
2438200.5	Jun 20			398.122	668321.12	194.82	
2438210.5	SUMMER Jun 30			407.854	668330.85	199.42	
2438220.5	Jul 10			417.587	668340.59	204.06	
2438230.5	Jul 20			427.319	668350.31	208.77	
2438240.5	Jul 30			437.052	668360.05	213.53	
2438250.5	Aug 9			446.784	668369.78	218.36	
2438260.5	Aug 19			456.517	668379.52	223.27	
2438270.5	Aug 29			466.249	668389.24	228.25	OCT 3-DEC 31. Mars not clearly visible from Earth for physical observations.
2438280.5	Sep 8			475.981	668398.98	233.31	
2438290.5	Sep 18			485.714	668408.71	238.45	
2438300.5	FALL Sep 28			495.446	668418.45	243.69	
2438310.5	Oct 8			505.179	668428.17	249.01	
2438320.5	Oct 18			514.911	668437.91	254.43	
2438330.5	Oct 28			524.644	668447.64	259.94	
2438340.5	Nov 7			534.376	668457.38	265.55	
2438350.5	Nov 17			FALL 544.109	668467.10	271.25	
2438360.5	Nov 27			553.841	668476.84	277.05	
2438370.5	Dec 7			563.573	668486.57	282.94	
2438380.5	Dec 17			573.306	668496.30	288.91	
2438390.5	WINTER Dec 27			583.038	668506.03	294.97	

Table A-1. Earth-Mars Calendar (continued)

EARTH			MARS				NOTES
J. D. Julian day	Northern hemisphere season and date	Year	Year	Northern hemisphere season and year day	Consecutive Mars day	Heliocentric ecliptic longitude, deg	
2438400.5	WINTER Jan 6	1964 (leap year)	999	FALL 592.771	668515.77	301.10	Jan 1-Jul 1. Mars not clearly visible from Earth for physical observations
2438410.5	Jan 16			602.503	668525.50	307.29	
2438420.5	Jan 26			612.236	668535.23	313.54	
2438430.5	Feb 5			621.968	668544.96	319.83	
2438440.5	Feb 15			631.701	668554.70	326.15	
2438450.5	Feb 25			641.433	668564.43	332.50	
2438460.5	Mar 6			651.165	668574.16	338.85	
2438470.5	Mar 16			660.898	668583.89	345.19	
2438480.5	SPRING Mar 26			1.630	668593.63	351.51	
2438490.5	Apr 5		1000 (leap year)	WINTER 11.363	668603.36	357.79	
2438500.5	Apr 15			21.095	668613.09	4.03	
2438510.5	Apr 25			30.828	668622.82	10.22	
2438520.5	May 5			40.560	668632.55	16.34	
2438530.5	May 15			50.293	668642.29	22.38	
2438540.5	May 25			60.025	668652.02	28.35	
2438550.5	Jun 4			69.757	668661.75	34.23	
2438560.5	Jun 14			79.490	668671.48	40.01	
2438570.5	SUMMER Jun 24			89.222	668681.22	45.71	
2438580.5	Jul 4			98.955	668690.95	51.31	
2438590.5	Jul 14			108.687	668700.68	56.81	
2438600.5	Jul 24			118.420	668710.41	62.22	
2438610.5	Aug 3	128.152		668720.15	67.54		
2438620.5	Aug 13	137.885		668729.88	72.77		
2438630.5	Aug 23	147.617		668739.61	77.91		
2438640.5	Sep 2	157.349		668749.34	82.96		
2438650.5	Sep 12	SPRING 167.082		668759.08	87.94		
2438660.5	Sep 22	176.814		668768.81	92.84		
2438670.5	FALL Oct 2	186.547		668778.54	97.67		
2438680.5	Oct 12	196.279		668788.27	102.43		
2438690.5	Oct 22	206.012		668798.01	107.13		
2438700.5	Nov 1	215.744		668807.74	111.77		
2438710.5	Nov 11	225.477		668817.47	116.37		
2438720.5	Nov 21	235.209		668827.20	120.91		
2438730.5	Dec 1	244.941		668836.94	125.42		
2438740.5	Dec 11	254.674		668846.67	129.89		
2438750.5	WINTER Dec 21	264.406		668856.41	134.33		
2438760.5	Dec 31	274.139		668866.13	138.75		
2438770.5	Jan 10	283.871		668875.87	143.14		
2438780.5	Jan 20	293.604		668885.60	147.52		
2438790.5	Jan 30	303.336		668895.34	151.90		
2438800.5	Feb 9	313.068		668905.06	156.26		
2438810.5	Feb 19	322.801		668914.80	160.63		
2438820.5	Mar 1	332.533		668924.53	165.00		
2438830.5	Mar 11	342.266		668934.27	169.39		
2438840.5	SPRING Mar 21	351.998		668943.99	173.79		
2438850.5	Mar 31	SUMMER 361.731		668953.73	178.21		
2438860.5	Apr 10	371.463		668963.46	182.66		
2438870.5	Apr 20	381.196		668973.20	187.14		
2438880.5	Apr 30	390.928		668982.92	191.66		
2438890.5	May 10	400.660		668992.66	196.22		
2438900.5	May 20	410.393		669002.39	200.83		
2438910.5	May 30	420.125		669012.13	205.50		
2438920.5	Jun 9	429.858		669021.85	210.22		
2438930.5	Jun 19	439.590		669031.59	215.00		
2438940.5	SUMMER Jun 29	449.323		669041.32	219.86		
2438950.5	Jul 9	459.055		669051.05	224.78		
2438960.5	Jul 19	468.788		669060.78	229.79		
2438970.5	Jul 29	478.520		669070.52	234.87		
2438980.5	Aug 8	488.252		669080.25	240.05		
2438990.5	Aug 18	497.985		669089.98	245.31		
2439000.5	Aug 28	507.717		669099.71	250.66		
2439010.5	Sep 7	517.450		669109.45	256.11		
2439020.5	Sep 17	527.182		669119.18	261.65		
2439030.5	FALL Sep 27	536.915		669128.91	267.29		
2439040.5	Oct 7	FALL 546.647		669138.64	273.03		
2439050.5	Oct 17	556.380		669148.38	278.86		
2439060.5	Oct 27	566.112		669158.11	284.77		
2439070.5	Nov 6	575.844		669167.84	290.77		
2439080.5	Nov 16	585.577		669177.57	296.85		
2439090.5	Nov 26	595.309		669187.30	303.00		
2439100.5	Dec 6	605.042		669197.04	309.22		
2439110.5	Dec 16	614.774		669206.77	315.48		
2439120.5	WINTER Dec 26	624.507		669216.50	321.78		

Table A-1. Earth-Mars Calendar (continued)

EARTH			MARS				NOTES
J. D. Julian day	Northern hemisphere season and date	Year	Year	Northern hemisphere season and year day	Consecutive Mars day	Heliocentric eccentric longitude, deg	
2439130.5	WINTER Jan 5	1966	1000 (leap year)	FALL 634.239	669226.23	328.12	Jan 2-Oct 1. Mars not clearly visible from Earth for physical observations.
2439140.5	Jan 15			643.972	669235.97	334.46	
2439150.5	Jan 25			653.704	669245.70	340.81	
2439160.5	Feb 4			663.436	669255.43	347.15	
2439170.5	Feb 14			4.169	669265.16	353.46	
2439180.5	Feb 24		1001 (leap year)	WINTER 13.901	669274.90	359.73	
2439190.5	Mar 6			23.634	669284.63	5.95	
2439200.5	Mar 16			33.366	669294.36	12.12	
2439210.5	SPRING Mar 26			43.099	669304.09	18.22	
2439220.5	Apr 5			52.831	669313.83	24.24	
2439230.5	Apr 15			62.564	669323.56	30.17	
2439240.5	Apr 25			72.296	669333.29	36.02	
2439250.5	May 5			82.028	669343.02	41.78	
2439260.5	May 15			91.761	669352.76	47.44	
2439270.5	May 25			101.493	669362.49	53.01	
2439280.5	Jun 4			111.226	669372.22	58.49	
2439290.5	Jun 14			120.958	669381.95	63.87	
2439300.5	SUMMER Jun 24			130.691	669391.69	69.16	
2439310.5	Jul 4			140.423	669401.42	74.36	
2439320.5	Jul 14			150.155	669411.15	79.47	
2439330.5	Jul 24			159.888	669420.88	84.50	
2439340.5	Aug 3			SPRING 169.620	669430.62	89.45	
2439350.5	Aug 13			179.353	669440.35	94.33	
2439360.5	Aug 23			189.085	669450.08	99.14	
2439370.5	Sep 2			198.818	669459.81	103.88	
2439380.5	Sep 12			208.550	669469.55	108.56	
2439390.5	Sep 22			218.283	669479.28	113.19	
2439400.5	FALL Oct 2			228.015	669489.01	117.77	
2439410.5	Oct 12			237.747	669498.74	122.31	
2439420.5	Oct 22			247.480	669508.48	126.80	
2439430.5	Nov 1			257.212	669518.21	131.26	
2439440.5	Nov 11			266.945	669527.94	135.70	
2439450.5	Nov 21			276.677	669537.67	140.11	
2439460.5	Dec 1			286.410	669547.41	144.50	
2439470.5	Dec 11			296.142	669557.14	148.87	
2439480.5	Dec 21			305.875	669566.87	153.24	
2439490.5	WINTER Dec 31	1967		315.607	669576.60	157.61	
2439500.5	Jan 10			325.339	669586.34	161.98	
2439510.5	Jan 20			335.072	669596.07	166.35	
2439520.5	Jan 30			344.804	669605.80	170.74	
2439530.5	Feb 9			354.537	669615.53	175.15	
2439540.5	Feb 19			SUMMER 364.269	669625.27	179.58	
2439550.5	Mar 1			374.002	669635.00	184.04	
2439560.5	Mar 11			383.734	669644.73	188.53	
2439570.5	SPRING Mar 21			393.467	669654.46	193.06	
2439580.5	Mar 31			403.199	669664.20	197.63	
2439590.5	Apr 10			412.931	669673.93	202.26	
2439600.5	Apr 20			422.664	669683.66	206.94	
2439610.5	Apr 30			432.396	669693.39	211.67	
2439620.5	May 10			442.129	669703.13	216.48	
2439630.5	May 20			451.861	669712.86	221.35	
2439640.5	May 30			461.594	669722.59	226.30	
2439650.5	Jun 9			471.326	669732.32	231.33	
2439660.5	Jun 19			481.059	669742.05	236.44	
2439670.5	SUMMER Jun 29			490.791	669751.79	241.64	
2439680.5	Jul 9			500.523	669761.52	246.92	
2439690.5	Jul 19			510.256	669771.25	252.30	
2439700.5	Jul 29			519.988	669780.98	257.78	
2439710.5	Aug 8			529.721	669790.72	263.35	
2439720.5	Aug 18			FALL 539.453	669800.45	269.02	
2439730.5	Aug 28			549.186	669810.18	274.78	
2439740.5	Sep 7			558.918	669819.91	280.64	
2439750.5	Sep 17			568.650	669829.65	286.58	
2439760.5	FALL Sep 27			578.383	669839.38	292.61	
2439770.5	Oct 7			588.115	669849.11	298.71	
2439780.5	Oct 17			597.848	669858.84	304.88	
2439790.5	Oct 27			607.580	669868.58	311.11	
2439800.5	Nov 6			617.313	669878.31	317.39	
2439810.5	Nov 16			627.045	669888.04	323.71	
2439820.5	Nov 26			636.778	669897.77	330.04	
2439830.5	Dec 6			646.510	669907.51	336.40	
2439840.5	Dec 16			656.242	669917.24	342.74	
2439850.5	WINTER Dec 26			665.975	669926.97	349.08	

Table A-1. Earth-Mars Calendar (continued)

EARTH			MARS				NOTES
J. D. Julian day	Northern hemisphere season and date	Year	Year	Northern hemisphere season and year day	Consecutive Mars day	Heliocentric ecliptic longitude, deg	
2439860.5	WINTER Jan 5	1968 (leap year)	1002	FALL 6.707	669936.70	355.38	
2439870.5	Jan 15			WINTER 16.440	669946.44	1.64	
2439880.5	Jan 25			26.172	669956.17	7.85	
2439890.5	Feb 4			35.905	669965.90	14.00	
2439900.5	Feb 14			45.637	669975.63	20.07	
2439910.5	Feb 24			55.370	669985.37	26.07	
2439920.5	Mar 5			65.102	669995.10	31.98	
2439930.5	Mar 15			74.834	670004.83	37.81	
2439940.5	SPRING Mar 25			84.567	670014.56	43.54	
2439950.5	Apr 4			94.299	670024.30	49.18	
2439960.5	Apr 14			104.032	670034.03	54.72	
2439970.5	Apr 24			113.764	670043.76	60.16	
2439980.5	May 4			123.497	670053.49	65.52	
2439990.5	May 14			133.229	670063.23	70.78	
2440000.5	May 24			142.962	670072.96	75.95	
2440010.5	Jun 3			152.694	670082.69	81.04	
2440020.5	Jun 13			162.426	670092.42	86.04	
2440030.5	SUMMER Jun 23			SPRING 172.159	670102.16	90.97	Apr 3-Sep 30. Mars not clearly visible from Earth for physical observations.
2440040.5	Jul 3			181.891	670111.89	95.83	
2440050.5	Jul 13			191.624	670121.62	100.61	
2440060.5	Jul 23			201.356	670131.35	105.34	
2440070.5	Aug 2			211.089	670141.09	110.00	
2440080.5	Aug 12			220.821	670150.82	114.62	
2440090.5	Aug 22			230.554	670160.55	119.18	
2440100.5	Sep 1			240.286	670170.28	123.70	
2440110.5	Sep 11			250.018	670180.02	128.19	
2440120.5	Sep 21			259.751	670189.75	132.64	
2440130.5	FALL Oct 1			269.483	670199.48	137.06	
2440140.5	Oct 11			279.216	670209.21	141.47	
2440150.5	Oct 21			288.948	670218.95	145.85	
2440160.5	Oct 31			298.681	670228.68	150.23	
2440170.5	Nov 10			308.413	670238.41	154.60	
2440180.5	Nov 20			318.146	670248.14	158.96	
2440190.5	Nov 30			327.878	670257.88	163.33	
2440200.5	Dec 10			337.610	670267.61	167.71	
2440210.5	Dec 20			347.343	670277.34	172.11	
2440220.5	WINTER Dec 30			357.075	670287.07	176.52	
2440230.5	Jan 9	1969		SUMMER 366.808	670296.80	180.96	
2440240.5	Jan 19			376.540	670306.54	185.42	
2440250.5	Jan 29			386.273	670316.27	189.93	
2440260.5	Feb 8			396.005	670326.00	194.47	
2440270.5	Feb 18			405.737	670335.73	199.06	
2440280.5	Feb 28			415.470	670345.47	203.70	Feb 23-Apr 8. Mariner-69 launch opportunity (Atlas-Centaur vehicle). Present plans allow for the launching of two spacecraft, one during the early and one during the late launch period within this opportunity.
2440290.5	Mar 10			425.202	670355.20	208.40	
2440300.5	SPRING Mar 20			434.935	670364.93	213.16	
2440310.5	Mar 30			444.667	670374.66	217.98	
2440320.5	Apr 9			454.400	670384.40	222.87	
2440330.5	Apr 19			464.132	670394.13	227.85	
2440340.5	Apr 29			473.865	670403.86	232.90	
2440350.5	May 9			483.597	670413.59	238.03	
2440360.5	May 19			493.329	670423.33	243.26	
2440370.5	May 29			503.062	670433.05	248.57	
2440380.5	Jun 8			512.794	670442.79	253.98	
2440390.5	Jun 18			522.527	670452.52	259.48	
2440400.5	SUMMER Jun 28			532.259	670462.26	265.08	
2440410.5	FALL Jul 8			541.992	670471.98	270.78	
2440420.5	Jul 18			551.724	670481.72	276.56	
2440430.5	Jul 28			561.457	670491.45	282.44	
2440440.5	Aug 7			571.189	670501.19	288.41	
2440450.5	Aug 17			580.921	670510.91	294.46	
2440460.5	Aug 27			590.654	670520.65	300.58	
2440470.5	Sep 6			600.386	670530.38	306.77	
2440480.5	Sep 16			610.119	670540.12	313.01	
2440490.5	FALL Sep 26			619.851	670549.84	319.30	
2440500.5	Oct 6			629.584	670559.58	325.63	
2440510.5	Oct 16			639.316	670569.31	331.97	
2440520.5	Oct 26			649.049	670579.05	338.32	
2440530.5	Nov 5			658.781	670588.77	344.66	
2440540.5	Nov 15		1003 (leap year)	668.513	670598.51	350.99	
2440550.5	Nov 25			678.246	670608.24	357.28	
2440560.5	Dec 5			WINTER 687.978	670617.98	3.53	
2440570.5	Dec 15			697.711	670627.70	9.72	
2440580.5	WINTER Dec 25			707.443	670637.44	15.85	

Table A-1. Earth-Mars Calendar (continued)

EARTH			MARS			Heliocentric ecliptic longitude, deg	NOTES
J. D. Julian day	Northern hemisphere season and date	Year	Year	Northern hemisphere season and year day	Consecutive Mars day		
2440590.5	WINTER Jan 4	1970	1003 (leap year)	WINTER 49.176	670647.17	21.90	Solar flare behavior varies according to the phase of the 11-year cycle. Thus the "solar maximum" behavior of 1959-1960 should be approximately repeated in 1970-1971.
2440600.5	Jan 14			58.908	670656.91	27.87	
2440610.5	Jan 24			68.641	670666.63	33.76	
2440620.5	Feb 3			78.373	670676.37	39.56	
2440630.5	Feb 13			88.105	670686.10	45.26	
2440640.5	Feb 23			97.838	670695.84	50.87	
2440650.5	Mar 5			107.570	670705.56	56.39	
2440660.5	Mar 15			117.303	670715.30	61.81	
2440670.5	SPRING Mar 25			127.035	670725.03	67.13	
2440680.5	Apr 4			136.768	670734.77	72.37	
2440690.5	Apr 14			146.500	670744.50	77.52	
2440700.5	Apr 24			156.233	670754.23	82.58	
2440710.5	May 4			165.965	670763.96	87.56	
2440720.5	May 14			175.697	670773.70	92.47	
2440730.5	May 24			185.430	670783.43	97.31	
2440740.5	Jun 3			195.162	670793.16	102.07	
2440750.5	Jun 13			204.895	670802.89	106.78	
2440760.5	SUMMER Jun 23			214.627	670812.63	111.43	
2440770.5	Jul 3			224.360	670822.36	116.03	
2440780.5	Jul 13			234.092	670832.09	120.58	
2440790.5	Jul 23			243.824	670841.82	125.09	
2440800.5	Aug 2			253.557	670851.55	129.57	
2440810.5	Aug 12			263.289	670861.29	134.01	
2440820.5	Aug 22			273.022	670871.02	138.43	
2440830.5	Sep 1			282.754	670880.75	142.82	
2440840.5	Sep 11			292.487	670890.48	147.21	
2440850.5	Sep 21			302.219	670900.22	151.58	
2440860.5	FALL Oct 1			311.952	670909.95	155.94	
2440870.5	Oct 11			321.684	670919.68	160.31	
2440880.5	Oct 21			331.416	670929.41	164.68	
2440890.5	Oct 31			341.149	670939.15	169.07	
2440900.5	Nov 10			350.881	670948.88	173.46	
2440910.5	Nov 20			360.614	670958.61	177.88	
2440920.5	SUMMER Nov 30			370.346	670968.34	182.33	
2440930.5	Dec 10			380.079	670978.08	186.81	
2440940.5	Dec 20			389.811	670987.80	191.32	
2440950.5	WINTER Dec 30			399.544	670997.54	195.88	
2440960.5	Jan 9	1971		409.276	671007.27	200.48	
2440970.5	Jan 19			419.008	671017.01	205.14	
2440980.5	Jan 29			428.741	671026.73	209.85	
2440990.5	Feb 8			438.473	671036.47	214.63	
2441000.5	Feb 18			448.206	671046.20	219.48	
2441010.5	Feb 28			457.938	671055.94	224.40	
2441020.5	Mar 10			467.671	671065.66	229.39	
2441030.5	Mar 20			477.403	671075.40	234.47	
2441040.5	SPRING Mar 30			487.136	671085.13	239.63	
2441050.5	Apr 9			496.868	671094.87	244.88	
2441060.5	Apr 19			506.600	671104.59	250.23	
2441070.5	Apr 29			516.333	671114.33	255.66	
2441080.5	May 9			526.065	671124.06	261.20	
2441090.5	May 19			535.798	671133.80	266.83	
2441100.5	FALL May 29			545.530	671143.52	272.55	
2441110.5	Jun 8			555.263	671153.26	278.37	
2441120.5	Jun 18			564.995	671162.99	284.27	
2441130.5	SUMMER Jun 28			574.728	671172.73	290.26	
2441140.5	Jul 8			584.460	671182.45	296.34	
2441150.5	Jul 18			594.192	671192.19	302.48	
2441160.5	Jul 28			603.925	671201.92	308.68	
2441170.5	Aug 7			613.657	671211.66	314.94	
2441180.5	Aug 17			623.390	671221.38	321.24	
2441190.5	Aug 27			633.122	671231.12	327.57	
2441200.5	Sep 6			642.855	671240.85	333.92	
2441210.5	Sep 16			652.587	671250.59	340.26	
2441220.5	FALL Sep 26			662.320	671260.31	346.60	
2441230.5	Oct 6		1004	3.052	671270.05	352.92	
2441240.5	WINTER Oct 16			12.784	671279.78	359.19	
2441250.5	Oct 26			22.517	671289.52	365.42	
2441260.5	Nov 5			32.249	671299.24	371.60	
2441270.5	Nov 15			41.982	671308.98	377.70	
2441280.5	Nov 25			51.714	671318.71	383.73	
2441290.5	Dec 5			61.447	671328.45	389.68	
2441300.5	Dec 15			71.179	671338.17	395.54	
2441310.5	WINTER Dec 25			80.911	671347.91	401.31	

AUG 10 PERIHELIC OPPOSITION

Earth-Mars distance at closest approach:
34.9 million mi (56.2 million km) —
exceptionally close approach.
Earth days until next opposition: 807.
Earth years until next exceptionally close
approach: 17.2 (Sep 28, 1988).

Table A-1. Earth-Mars Calendar (continued)

EARTH			MARS			Heliocentric ecliptic longitude, deg	NOTES
J.D. Julian day	Northern hemisphere season and date	Year	Year	Northern hemisphere season and year day	Consecutive Mars day		
2441320.5	WINTER Jan 4	1972 (leap year)	1994	WINTER 90.644	671357.64	46.28	OCT 25, OPPOSITION Earth-Mars distance at closest approach: 10.4 million mi (16.6 million km) Earth days until next opposition: 794
2441330.5	Jan 14			100.376	671367.38	52.56	
2441340.5	Jan 24			110.109	671377.10	58.05	
2441350.5	Feb 3			119.841	671386.84	63.44	
2441360.5	Feb 13			129.574	671396.57	68.74	
2441370.5	Feb 23			139.306	671406.30	73.95	
2441380.5	Mar 4			149.039	671416.03	79.07	
2441390.5	Mar 14			158.771	671425.77	84.11	
2441400.5	SPRING Mar 24			SPRING 168.503	671435.50	89.07	
2441410.5	Apr 3			178.236	671445.23	93.95	
2441420.5	Apr 13	187.968	671454.96	98.77			
2441430.5	Apr 23	197.701	671464.70	103.52			
2441440.5	May 3	207.433	671474.43	108.21			
2441450.5	May 13	217.166	671484.16	112.84			
2441460.5	May 23	226.898	671493.89	117.43			
2441470.5	Jun 2	236.631	671503.63	121.97			
2441480.5	Jun 12	246.363	671513.36	126.47			
2441490.5	SUMMER Jun 22	256.095	671523.09	130.93			
2441500.5	Jul 2	265.828	671532.82	135.37			
2441510.5	Jul 12	275.560	671542.55	139.78			
2441520.5	Jul 22	285.293	671552.29	144.17			
2441530.5	Aug 1	295.025	671562.02	148.55			
2441540.5	Aug 11	304.758	671571.75	152.92			
2441550.5	Aug 21	314.490	671581.48	157.29			
2441560.5	Aug 31	324.223	671591.22	161.66			
2441570.5	Sep 10	333.955	671600.95	166.03			
2441580.5	Sep 20	343.687	671610.68	170.42			
2441590.5	FALL Sep 30	353.420	671620.41	174.82			
2441600.5	Oct 10	SUMMER 363.152	671630.15	179.25			
2441610.5	Oct 20	372.885	671639.88	183.70			
2441620.5	Oct 30	382.617	671649.62	188.19			
2441630.5	Nov 9	392.350	671659.34	192.72			
2441640.5	Nov 19	402.082	671669.08	197.29			
2441650.5	Nov 29	411.815	671678.81	201.93			
2441660.5	Dec 9	421.547	671688.55	206.58			
2441670.5	Dec 19	431.279	671698.27	211.31			
2441680.5	WINTER Dec 29	441.012	671708.01	216.11			
2441690.5	Jan 8	450.744	671717.74	220.97			
2441700.5	Jan 18	460.477	671727.48	225.91			
2441710.5	Jan 28	470.209	671737.20	230.93			
2441720.5	Feb 7	479.942	671746.94	236.04			
2441730.5	Feb 17	489.674	671756.67	241.22			
2441740.5	Feb 27	499.407	671766.41	246.50			
2441750.5	Mar 9	509.139	671776.13	251.87			
2441760.5	Mar 19	518.871	671785.87	257.34			
2441770.5	SPRING Mar 29	528.604	671795.60	262.90			
2441780.5	Apr 8	FALL 538.336	671805.34	268.56			
2441790.5	Apr 18	548.069	671815.06	274.31			
2441800.5	Apr 28	557.801	671824.80	280.16			
2441810.5	May 8	567.534	671834.53	286.09			
2441820.5	May 18	577.266	671844.27	292.11			
2441830.5	May 28	586.998	671853.99	298.20			
2441840.5	Jun 7	596.731	671863.73	304.37			
2441850.5	Jun 17	606.463	671873.46	310.59			
2441860.5	SUMMER Jun 27	616.196	671883.20	316.86			
2441870.5	Jul 7	625.928	671892.92	323.18			
2441880.5	Jul 17	635.661	671902.66	329.51			
2441890.5	Jul 27	645.393	671912.39	335.86			
2441900.5	Aug 6	655.126	671922.13	342.21			
2441910.5	Aug 16	664.858	671931.85	348.54			
2441920.5	Aug 26	674.590	671941.59	354.85			
2441930.5	Sep 5	WINTER 684.323	671951.32	1.11			
2441940.5	Sep 15	694.055	671961.05	7.33			
2441950.5	FALL Sep 25	703.788	671970.78	13.48			
2441960.5	Oct 5	713.520	671980.52	19.56			
2441970.5	Oct 15	723.253	671990.25	25.57			
2441980.5	Oct 25	732.985	671999.98	31.49			
2441990.5	Nov 4	742.718	672009.71	37.32			
2442000.5	Nov 14	752.450	672019.45	43.06			
2442010.5	Nov 24	762.182	672029.18	48.79			
2442020.5	Dec 4	771.915	672038.91	54.25			
2442030.5	Dec 14	781.647	672048.64	59.71			
2442040.5	WINTER Dec 24	791.380	672058.38	65.07			

Table A-1. Earth-Mars Calendar (continued)

EARTH			MARS			Heliocentric ecliptic longitude, deg	NOTES
J.D. Julian day	Northern hemisphere season and date	Year	Year	Northern hemisphere season and year day	Consecutive Mars day		
2442050.5	WINTER Jan 3	1974	1005 (leap year)	WINTER 133.112	672068.11	70.34	
2442060.5	Jan 13			142.845	672077.84	75.53	
2442070.5	Jan 23			152.577	672087.57	80.62	
2442080.5	Feb 2			162.310	672097.30	85.64	
2442090.5	Feb 12			SPRING 172.042	672107.04	90.57	
2442100.5	Feb 22			181.774	672116.77	95.44	
2442110.5	Mar 4			191.507	672126.50	100.23	
2442120.5	Mar 14			201.239	672136.23	104.96	
2442130.5	SPRING Mar 24			210.972	672145.97	109.64	
2442140.5	Apr 3			220.704	672155.70	114.25	
2442150.5	Apr 13			230.437	672165.43	118.83	
2442160.5	Apr 23			240.169	672175.16	123.35	
2442170.5	May 3			249.902	672184.90	127.84	
2442180.5	May 13			259.634	672194.63	132.30	
2442190.5	May 23			269.366	672204.36	136.72	
2442200.5	Jun 2			279.099	672214.09	141.13	
2442210.5	Jun 12			288.831	672223.83	145.52	
2442220.5	SUMMER Jun 22			298.564	672233.56	149.89	
2442230.5	Jul 2			308.296	672243.29	154.26	
2442240.5	Jul 12			318.029	672253.02	158.63	
2442250.5	Jul 22			327.761	672262.76	163.00	
2442260.5	Aug 1			337.493	672272.49	167.38	
2442270.5	Aug 11			347.226	672282.22	171.77	
2442280.5	Aug 21			356.958	672291.95	176.18	
2442290.5	Aug 31			SUMMER 366.691	672301.69	180.62	
2442300.5	Sep 10			376.423	672311.42	185.08	
2442310.5	Sep 20			386.156	672321.15	189.58	
2442320.5	FALL Sep 30			395.888	672330.88	194.12	
2442330.5	Oct 10			405.621	672340.62	198.71	
2442340.5	Oct 20			415.353	672350.35	203.34	
2442350.5	Oct 30			425.085	672360.08	208.03	
2442360.5	Nov 9			434.818	672369.81	212.79	
2442370.5	Nov 19			444.550	672379.55	217.60	
2442380.5	Nov 29			454.283	672389.28	222.49	
2442390.5	Dec 9			464.015	672399.01	227.45	
2442400.5	Dec 19			473.748	672408.74	232.50	
2442410.5	WINTER Dec 29			483.480	672418.48	237.62	
2442420.5	Jan 8	1975		493.213	672428.21	242.84	
2442430.5	Jan 18			502.945	672437.94	248.15	
2442440.5	Jan 28			512.677	672447.67	253.54	
2442450.5	Feb 7			522.410	672457.41	259.04	
2442460.5	Feb 17			532.142	672467.14	264.63	
2442470.5	Feb 27			FALL 541.875	672476.87	270.31	
2442480.5	Mar 9			551.607	672486.60	276.09	
2442490.5	Mar 19			561.340	672496.34	281.96	
2442500.5	SPRING Mar 29			571.072	672506.07	287.92	
2442510.5	Apr 8			580.805	672515.80	293.96	
2442520.5	Apr 18			590.537	672525.53	300.07	
2442530.5	Apr 28			600.269	672535.27	306.26	
2442540.5	May 8			610.002	672545.00	312.49	
2442550.5	May 18			619.734	672554.73	318.78	
2442560.5	May 28			629.467	672564.46	325.10	
2442570.5	Jun 7			639.199	672574.20	331.44	
2442580.5	Jun 17			648.932	672583.93	337.79	
2442590.5	SUMMER Jun 27			658.664	672593.66	344.13	
2442600.5	Jul 7			668.397	672603.39	350.46	
2442610.5	Jul 17		1006	9.129	672613.13	356.76	
2442620.5	Jul 27			WINTER 18.861	672622.86	3.01	
2442630.5	Aug 6			28.594	672632.59	9.21	
2442640.5	Aug 16			38.326	672642.32	15.34	
2442650.5	Aug 26			48.059	672652.05	21.40	
2442660.5	Sep 5			57.791	672661.79	27.38	
2442670.5	Sep 15			67.524	672671.52	33.28	
2442680.5	FALL Sep 25			77.256	672681.25	39.08	
2442690.5	Oct 5			86.989	672690.98	44.80	
2442700.5	Oct 15			96.721	672700.72	50.42	
2442710.5	Oct 25			106.453	672710.45	55.94	
2442720.5	Oct 31			116.186	672720.18	61.37	
2442730.5	Nov 4			125.918	672729.91	66.70	
2442740.5	Nov 14			135.651	672739.65	71.95	
2442750.5	Nov 24			145.383	672749.38	77.10	
2442760.5	Dec 4			155.116	672759.11	82.17	
2442770.5	WINTER Dec 14			164.848	672768.84	87.16	
2442780.5	Dec 24						

DEC 15. OPPOSITION

Earth-Mars distance at closest approach:
52.4 million mi (84.4 million km).
Earth days until next opposition: 771.

Table A-1. Earth-Mars Calendar (continued)

EARTH			MARS				NOTES
J. D. Julian day	Northern hemisphere season and date	Year	Year	Northern hemisphere season and year day	Consecutive Mars day	Heliocentric ecliptic longitude, deg	
2442780.5	WINTER Jan 3	1976 (leap year)	1006	SPRING 174.580	672778.58	92.08	
2442790.5	Jan 13			184.313	672788.31	96.92	
2442800.5	Jan 23			194.045	672798.04	101.70	
2442810.5	Feb 2			203.778	672807.77	106.41	
2442820.5	Feb 12			213.510	672817.51	111.06	
2442830.5	Feb 22			223.243	672827.24	115.67	
2442840.5	Mar 3			232.975	672836.97	120.22	
2442850.5	Mar 13			242.708	672846.70	124.74	
2442860.5	SPRING Mar 23			252.440	672856.44	129.21	
2442870.5	Apr 2			262.172	672866.17	133.66	
2442880.5	Apr 12			271.905	672875.90	138.08	
2442890.5	Apr 22			281.637	672885.63	142.48	
2442900.5	May 2			291.370	672895.37	146.86	
2442910.5	May 12			301.102	672905.10	151.24	
2442920.5	May 22			310.835	672914.83	155.60	
2442930.5	Jun 1			320.567	672924.56	159.97	
2442940.5	Jun 11			330.300	672934.30	164.34	
2442950.5	SUMMER Jun 21			340.032	672944.03	168.73	
2442960.5	Jul 1			349.764	672953.76	173.12	
2442970.5	Jul 11			359.497	672963.49	177.54	
2442980.5	Jul 21			SUMMER 369.229	672973.23	181.99	
2442990.5	Jul 31			378.962	672982.96	186.46	
2443000.5	Aug 10			388.694	672992.69	190.97	
2443010.5	Aug 20			398.427	673002.42	195.53	
2443020.5	Aug 30			408.159	673012.16	200.13	
2443030.5	Sep 9			417.892	673021.89	204.78	
2443040.5	Sep 19			427.624	673031.62	209.49	
2443050.5	FALL Sep 29			437.356	673041.35	214.26	
2443060.5	Oct 9			447.089	673051.09	219.10	
2443070.5	Oct 19			456.821	673060.82	224.01	
2443080.5	Oct 29			466.554	673070.55	229.00	
2443090.5	Nov 8			476.286	673080.28	234.07	
2443100.5	Nov 18			486.019	673090.02	239.22	
2443110.5	Nov 28			495.751	673099.75	244.47	
2443120.5	Dec 8			505.484	673109.48	249.80	
2443130.5	Dec 18			515.216	673119.21	255.23	
2443140.5	WINTER Dec 28			524.948	673128.95	260.76	
2443150.5	Jan 7	1977		534.681	673138.68	266.38	
2443160.5	Jan 17			FALL 544.413	673148.41	272.09	
2443170.5	Jan 27			554.146	673158.14	277.90	
2443180.5	Feb 6			563.878	673167.88	283.80	
2443190.5	Feb 16			573.611	673177.61	289.78	
2443200.5	Feb 26			583.343	673187.34	295.85	
2443210.5	Mar 8			593.076	673197.07	301.98	
2443220.5	Mar 18			602.808	673206.80	308.18	
2443230.5	SPRING Mar 28			612.540	673216.54	314.44	
2443240.5	Apr 7			622.273	673226.27	320.73	
2443250.5	Apr 17			632.005	673236.00	327.06	
2443260.5	Apr 27			641.738	673245.73	333.40	
2443270.5	May 7			651.470	673255.47	339.75	
2443280.5	May 17			661.203	673265.20	346.09	
2443290.5	May 27		1007 (leap year)	2.935	673274.93	352.41	
2443300.5	Jun 6			WINTER 12.667	673284.66	358.69	
2443310.5	Jun 16			22.400	673294.40	4.92	
2443320.5	SUMMER Jun 26			32.132	673304.13	11.10	
2443330.5	Jul 6			41.865	673313.86	17.21	
2443340.5	Jul 16			51.597	673323.59	23.25	
2443350.5	Jul 26			61.330	673333.33	29.20	
2443360.5	Aug 5			71.062	673343.05	35.07	
2443370.5	Aug 15			80.795	673352.79	40.85	
2443380.5	Aug 25			90.527	673362.52	46.53	
2443390.5	Sep 4			100.259	673372.26	52.12	
2443400.5	Sep 14			109.992	673381.98	57.61	
2443410.5	FALL Sep 24			119.724	673391.72	63.01	
2443420.5	Oct 4			129.457	673401.45	68.32	
2443430.5	Oct 14			139.189	673411.19	73.54	
2443440.5	Oct 24			148.922	673420.91	78.67	
2443450.5	Nov 3			158.654	673430.65	83.71	
2443460.5	Nov 13			SPRING 168.387	673440.38	88.68	
2443470.5	Nov 23			178.119	673450.12	93.57	
2443480.5	Dec 3			187.851	673459.84	98.39	
2443490.5	Dec 13			197.584	673469.58	103.15	
2443500.5	WINTER Dec 23			207.316	673479.31	107.85	

Table A-1. Earth-Mars Calendar (continued)

EARTH			MARS			NOTES
J.D. Julian day	Northern hemisphere season and date	Year	Northern hemisphere season and year (date)	Conjunction Mars day	Heliocentric longitude, deg	
2443510.5	WINTER Jan. 2	1978	Spring (Leap year)	217.039	673489.59	112.43
2443520.5	Jan. 12			226.781	673498.37	117.67
2443530.5	Jan. 22			236.514	673508.51	121.42
2443540.5	Feb. 1			246.246	673518.24	126.12
2443550.5	Feb. 11			255.979	673527.93	130.59
2443560.5	Feb. 21			265.711	673537.71	135.03
2443570.5	Mar. 3			275.443	673547.44	139.44
2443580.5	Mar. 13			285.175	673557.17	143.83
2443590.5	SPRING Mar. 23			294.908	673566.91	148.21
2443600.5	Apr. 2			304.641	673576.64	152.58
2443610.5	Apr. 12			314.373	673586.37	156.95
2443620.5	Apr. 22			324.106	673596.10	161.32
2443630.5	May 2			333.838	673605.84	165.69
2443640.5	May 12			343.571	673615.57	170.07
2443650.5	May 22			353.303	673625.30	174.48
2443660.5	SUMMER	1978	SUMMER	363.035	673635.03	178.90
2443670.5				372.768	673644.77	183.35
2443680.5				382.500	673654.50	187.84
2443690.5				392.233	673664.23	192.46
2443700.5				401.965	673673.96	196.93
2443710.5				411.698	673683.70	201.54
2443720.5				421.430	673693.43	206.21
2443730.5				431.163	673703.16	210.93
2443740.5				440.895	673712.89	215.73
2443750.5				450.627	673722.63	220.58
2443760.5				460.359	673732.36	225.52
2443770.5				470.092	673742.09	230.53
2443780.5				479.825	673751.82	235.62
2443790.5				489.557	673761.55	240.80
2443800.5	FALL	1978	FALL	499.290	673771.29	246.08
2443810.5				509.022	673781.02	251.44
2443820.5				518.754	673790.75	256.90
2443830.5				528.487	673800.48	262.45
2443840.5				538.219	673810.22	268.10
2443850.5				547.952	673819.95	273.84
2443860.5				557.684	673829.68	279.68
2443870.5				567.417	673839.41	285.61
2443880.5				577.149	673849.15	291.62
2443890.5				586.882	673858.88	297.71
2443900.5				596.614	673868.61	303.86
2443910.5				606.346	673878.34	310.08
2443920.5				616.079	673888.08	316.35
2443930.5				625.811	673897.80	322.66
2443940.5	SPRING	1979	SPRING	635.544	673907.54	329.00
2443950.5				645.276	673917.27	335.35
2443960.5				655.009	673927.01	341.70
2443970.5				664.741	673936.73	348.03
2443980.5				674.474	673946.47	354.34
2443990.5			WINTER	684.206	673956.20	0.62
2444000.5				693.938	673965.94	6.84
2444010.5				703.671	673975.66	13.00
2444020.5				713.403	673985.40	19.09
2444030.5				723.136	673995.13	25.10
2444040.5				732.868	674004.87	31.03
2444050.5			SUMMER	742.601	674014.59	36.87
2444060.5				752.333	674024.33	42.62
2444070.5				762.066	674034.06	48.27
2444080.5				771.798	674043.80	53.83
2444090.5				781.530	674053.52	59.30
2444100.5				791.263	674063.26	64.67
2444110.5				801.005	674072.99	69.95
2444120.5				810.728	674082.73	75.14
2444130.5				820.460	674092.45	80.24
2444140.5	FALL	1979	FALL	830.193	674102.19	85.26
2444150.5			SPRING	839.925	674111.92	90.21
2444160.5				849.658	674121.66	95.08
2444170.5				859.390	674131.38	99.88
2444180.5				869.122	674141.12	104.61
2444190.5				878.855	674150.85	109.29
2444200.5				888.587	674160.59	113.91
2444210.5				898.320	674170.31	118.49
2444220.5				908.052	674180.05	123.02
2444230.5			WINTER	917.785	674189.78	127.51
2444240.5				927.517	674199.51	131.95
2444250.5				937.250	674209.25	136.34
2444260.5				946.982	674218.98	140.68
2444270.5				956.715	674228.71	144.97
2444280.5				966.447	674238.44	149.21

Table A-1. Earth-Mars Calendar (continued)

EARTH			MARS				NOTES
J. D. Julian day	Northern hemisphere season and date	Year	Year	Northern hemisphere season and year day	Consecutive Mars day	Heliocentric ecliptic longitude, deg	
2444240.5	WINTER Jan 2	1980 (leap year)	1008	SPRING 258.517	674199.52	131.97	FEB 25. APHELIC OPPOSITION Earth-Mars distance at closest approach: 63.2 million mi (101.7 million km).
2444250.5	Jan 12			268.250	674209.24	136.40	
2444260.5	Jan 22			277.982	674218.98	140.80	
2444270.5	Feb 1			287.714	674228.71	145.19	
2444280.5	Feb 11			297.447	674238.45	149.57	
2444290.5	Feb 21			307.179	674248.17	153.94	
2444300.5	Mar 2			316.912	674257.91	158.30	
2444310.5	Mar 12			326.644	674267.64	162.67	
2444320.5	SPRING Mar 22			336.377	674277.38	167.05	
2444330.5	Apr 1			346.109	674287.10	171.44	
2444340.5	Apr 11			355.841	674296.84	175.85	
2444350.5	Apr 21			SUMMER 365.574	674306.57	180.28	
2444360.5	May 1	375.306	674316.30	184.74			
2444370.5	May 11	385.039	674326.03	189.24			
2444380.5	May 21	394.771	674335.77	193.77			
2444390.5	May 31	404.504	674345.50	198.35			
2444400.5	Jun 10	414.236	674355.23	202.98			
2444410.5	Jun 20	423.969	674364.96	207.66			
2444420.5	SUMMER Jun 30	433.701	674374.70	212.41			
2444430.5	Jul 10	443.433	674384.43	217.22			
2444440.5	Jul 20	453.166	674394.16	222.10			
2444450.5	Jul 30	462.898	674403.89	227.05			
2444460.5	Aug 9	472.631	674413.63	232.09			
2444470.5	Aug 19	482.363	674423.36	237.21			
2444480.5	Aug 29	492.096	674433.09	242.41			
2444490.5	Sep 8	501.828	674442.82	247.71			
2444500.5	Sep 18	511.561	674452.55	253.10			
2444510.5	FALL Sep 28	521.293	674462.29	258.58			
2444520.5	Oct 8	531.025	674472.02	264.16			
2444530.5	Oct 18	FALL 540.758	674481.76	269.84			
2444540.5	Oct 28	550.490	674491.48	275.61			
2444550.5	Nov 7	560.223	674501.22	281.47			
2444560.5	Nov 17	569.955	674510.95	287.42			
2444570.5	Nov 27	579.688	674520.69	293.45			
2444580.5	Dec 7	589.420	674530.41	299.56			
2444590.5	Dec 17	599.153	674540.15	305.74			
2444600.5	WINTER Dec 27	608.885	674549.88	311.98			
2444610.5	Jan 6	618.617	674559.62	318.26			
2444620.5	Jan 16	628.350	674569.34	324.58			
2444630.5	Jan 26	638.082	674579.08	330.92			
2444640.5	Feb 5	647.815	674588.81	337.27			
2444650.5	Feb 15	657.547	674598.55	343.61			
2444660.5	Feb 25	667.280	674608.27	349.94			
2444670.5	Mar 7	677.012	674618.01	356.24			
2444680.5	Mar 17	1009 (leap year)	WINTER 18.745	674627.74	2.50		
2444690.5	SPRING Mar 27	28.477	674637.48	8.71			
2444700.5	Apr 6	38.209	674647.20	14.85			
2444710.5	Apr 16	47.942	674656.94	20.92			
2444720.5	Apr 26	57.674	674666.67	26.91			
2444730.5	May 6	67.407	674676.41	32.81			
2444740.5	May 16	77.139	674686.13	38.63			
2444750.5	May 26	86.872	674695.87	44.35			
2444760.5	Jun 5	96.604	674705.60	49.98			
2444770.5	Jun 15	106.336	674715.34	55.51			
2444780.5	SUMMER Jun 25	116.069	674725.06	60.95			
2444790.5	Jul 5	125.801	674734.80	66.30			
2444800.5	Jul 15	135.534	674744.53	71.55			
2444810.5	Jul 25	145.266	674754.27	76.72			
2444820.5	Aug 4	154.999	674763.99	81.80			
2444830.5	Aug 14	164.731	674773.73	86.79			
2444840.5	Aug 24	SPRING 174.464	674783.46	91.72			
2444850.5	Sep 3	184.196	674793.20	96.57			
2444860.5	Sep 13	193.928	674802.92	101.45			
2444870.5	FALL Sep 23	203.661	674812.66	106.07			
2444880.5	Oct 3	213.393	674822.39	110.75			
2444890.5	Oct 13	223.126	674832.13	115.33			
2444900.5	Oct 23	232.858	674841.85	119.90			
2444910.5	Nov 2	242.591	674851.59	124.41			
2444920.5	Nov 12	252.323	674861.32	128.89			
2444930.5	Nov 22	262.056	674871.05	133.34			
2444940.5	Dec 2	271.788	674880.78	137.77			
2444950.5	Dec 12	281.520	674890.52	142.17			
2444960.5	WINTER Dec 22	291.253	674900.25	146.55			

Table A-1. Earth-Mars Calendar (continued)

EARTH			MARS				NOTES
J.D. Julian day	Northern hemisphere season and date	Year	Year	Northern hemisphere season and year day	Consecutive Mars day	Heliocentric ecliptic longitude, deg	
2444970.5	WINTER Jan 1	1982	1009 (leap year)	SPRING 300.985	674909.98	150.92	
2444980.5	Jan 11			310.718	674919.71	155.29	
2444990.5	Jan 21			320.450	674929.45	159.66	
2445000.5	Jan 31			330.183	674939.18	164.03	
2445010.5	Feb 10			339.915	674948.91	168.41	
2445020.5	Feb 20			349.648	674958.64	172.80	
2445030.5	Mar 2			359.380	674968.38	177.22	
2445040.5	Mar 12			SUMMER 369.112	674978.11	181.66	
2445050.5	SPRING Mar 22			378.845	674987.84	186.13	
2445060.5	Apr 1			388.577	674997.57	190.64	
2445070.5	Apr 11			398.310	675007.30	195.19	
2445080.5	Apr 21			408.042	675017.04	199.78	
2445090.5	May 1			417.775	675026.77	204.43	
2445100.5	May 11			427.507	675036.50	209.13	
2445110.5	May 21			437.240	675046.23	213.89	
2445120.5	May 31			446.972	675055.97	218.73	
2445130.5	Jun 10			456.704	675065.70	223.63	
2445140.5	Jun 20			466.437	675075.43	228.61	
2445150.5	SUMMER Jun 30			476.169	675085.16	233.67	
2445160.5	Jul 10			485.902	675094.90	238.81	
2445170.5	Jul 20			495.634	675104.63	244.05	
2445180.5	Jul 30			505.367	675114.36	249.37	
2445190.5	Aug 9			515.099	675124.09	254.79	
2445200.5	Aug 19			524.832	675133.83	260.30	
2445210.5	Aug 29			534.564	675143.56	265.91	
2445220.5	Sep 8			FALL 544.296	675153.29	271.62	
2445230.5	Sep 18			554.029	675163.02	277.41	
2445240.5	FALL Sep 28			563.761	675172.76	283.30	
2445250.5	Oct 8			573.494	675182.49	289.28	
2445260.5	Oct 18			583.226	675192.22	295.33	
2445270.5	Oct 28			592.959	675201.95	301.46	
2445280.5	Nov 7			602.691	675211.69	307.66	
2445290.5	Nov 17			612.423	675221.42	313.90	
2445300.5	Nov 27			622.156	675231.15	320.20	
2445310.5	Dec 7			631.888	675240.88	326.52	
2445320.5	Dec 17			641.621	675250.62	332.86	
2445330.5	WINTER Dec 27			651.353	675260.35	339.21	
2445340.5	Jan 6	1983	1010 (leap year)	661.086	675270.08	345.55	
2445350.5	Jan 16			671.818	675279.81	351.87	
2445360.5	Jan 26			WINTER 11.551	675289.55	358.16	
2445370.5	Feb 5			21.283	675299.28	4.40	
2445380.5	Feb 15			31.014	675309.01	10.59	
2445390.5	Feb 25			40.747	675318.74	16.71	
2445400.5	Mar 7			50.479	675328.48	22.75	
2445410.5	Mar 17			60.212	675338.21	28.71	
2445420.5	SPRING Mar 27			69.944	675347.94	34.59	
2445430.5	Apr 6			79.677	675357.67	40.38	
2445440.5	Apr 16			89.409	675367.41	46.07	
2445450.5	Apr 26			99.142	675377.14	51.67	
2445460.5	May 6			108.874	675386.87	57.18	
2445470.5	May 16			118.606	675396.60	62.59	
2445480.5	May 26			128.339	675406.34	67.90	
2445490.5	Jun 5			138.071	675416.07	73.13	
2445500.5	Jun 15			147.804	675425.80	78.27	
2445510.5	SUMMER Jun 25			157.536	675435.53	83.33	
2445520.5	Jul 5			SPRING 167.269	675445.27	88.30	
2445530.5	Jul 15			177.001	675455.00	93.20	
2445540.5	Jul 25			186.734	675464.73	98.03	
2445550.5	Aug 4			196.466	675474.46	102.80	
2445560.5	Aug 14			206.198	675484.20	107.50	
2445570.5	Aug 24			215.931	675493.93	112.14	
2445580.5	Sep 3			225.663	675503.66	116.74	
2445590.5	Sep 13			235.396	675513.39	121.28	
2445600.5	FALL Sep 23			245.128	675523.13	125.79	
2445610.5	Oct 3			254.861	675532.86	130.26	
2445620.5	Oct 13			264.593	675542.59	134.70	
2445630.5	Oct 23			274.326	675552.32	139.12	
2445640.5	Nov 2			284.058	675562.05	143.52	
2445650.5	Nov 12			293.790	675571.79	147.90	
2445660.5	Nov 22			303.523	675581.52	152.27	
2445670.5	Dec 2			313.255	675591.25	156.64	
2445680.5	Dec 12			322.988	675600.98	161.00	
2445690.5	WINTER Dec 22			332.720	675610.72	165.38	

APPENDIX B

GLOSSARY

Apparent Position	In astronomy, the position of a celestial body as seen from the center of the Earth or a planet.
Apsides	The end points of the major axis of an elliptical orbit.
Areocentric	Mars-centered. (Derived from "Ares," Greek word for Mars, the god of war.)
Areocentric Declination of the Earth (D_E)	On an areocentric sphere, the angular distance of the Earth from the Martian equator, measured from 0 to 90°, + to the north and - to the south of the equator.
Areocentric Latitude	The angle at the center of Mars between the equatorial plane and the straight line drawn to a given point. Counted from 0 to 90°, + or - according to northward or southward orientation of the line.
Areocentric Longitude of the Sun (L_S)	The longitude of the Sun on an areocentric sphere measured in the Mars orbital plane from its vernal equinox westward from 0 to 360°. It is equal to the heliocentric orbital longitude of Mars measured from its autumnal equinox.
Areographic = Areodetic } Latitude	The angle between the equatorial plane of Mars and the normal to the reference ellipsoid (or spheroid) at a given point on Mars' surface. Counted from 0 to 90°, + or - according to northward or southward orientation of the normal.
Areographic = Areodetic } Longitude	The angle between the reference meridian (plane) or prime meridian, and the meridian (plane) at a given point on Mars' surface. Counted from 0 to 360° westward; i.e., clockwise as viewed from the Mars' north pole, or opposite to Mars' rotation sense.
Areocentric Right Ascension of the Earth (A_E)	On an areocentric sphere, the angular distance in the Martian equatorial plane, measured from 0 to 360° eastward from the Martian vernal equinox to the great circle through the Earth and the Mars' celestial poles.

Aphelion	The point on a heliocentric orbit that is furthest from the Sun.
Argument	Arc, angle, angular distance, longitude.
Ascending Node	The intersection point of the orbit and reference great circles on the celestial sphere where the body (planet or satellite) moves from the southern into the northern hemisphere.
Astronomical Unit	The fundamental unit of distance used in astronomy. It is defined as "the unit of distance in terms of which, in Kepler's Third Law $n^2 a^3 = k^2 (1+m)$, the semimajor axis a of an elliptical orbit must be expressed in order that the Gaussian constant k may be exactly 0.01720209895, when the unit of time is the ephemeris day" (Explan. Suppl., 1961). Here n is the angular mean motion of any planet in radians per day, and m the ratio of the mass of the planet to the mass of the Sun. The AU is close to but not identical with the mean distance Earth-Sun. (For Earth, $a \approx 1.00000003$ AU.) For calculations, a rounded value of 1 AU = 1.496×10^8 km (based on radar measurements) has been adopted by the IAU Assembly in Hamburg, 1964, and introduced in all national ephemerides as of 1968.
Barycenter	Center of mass of a group of bodies.
Celestial Equator	The great circle of the celestial sphere marking its intersection with the extended equatorial plane of the Earth.
Celestial Latitude	The arc along a great circle perpendicular to the ecliptic between the ecliptic and the body, measured from 0 to 90° positively to the north and negatively to the south of the ecliptic. Or (more simply): the angular distance north or south of the ecliptic.
Celestial Longitude	The angle at the ecliptic pole, or the arc of the ecliptic, between the circle of celestial latitude of the vernal equinox and the circle of celestial latitude of the body, measured from 0 to 360° eastward from equinox. Or (more simply): the angular distance east of the vernal equinox along the ecliptic. Note: Celestial latitude and longitude of a body are its celestial coordinates in the 'ecliptic' system.

Celestial Meridian	The hour circle containing the zenith. Also called the meridian.
Celestial Poles	The points of the celestial sphere which are the intersections with the extended rotation axis of the Earth (or planet).
Celestial Sphere	The imaginary sphere of infinite radius surrounding the observer and upon which all celestial bodies (except that of the observer) may be projected.
Central Meridian	The fictitious meridian bisecting a planetary disk as seen externally.
Circle of Celestial Latitude	A great circle of the celestial sphere through the ecliptic poles for the Earth.
Declination	The arc along an hour circle from the celestial equator to the body in question measured from 0 to 90° positively to the north and negatively to the south of the equator. Or: angular distance north or south of the celestial equator.
Descending Node	Same as for ascending node except: from northern into southern.
Eccentric Anomaly	The angle described by the radius from center of the orbital ellipse to the projection of the planet (or satellite) onto the auxiliary circle of the ellipse and counted from perihelion (or perifocus) position in the direction of motion.
Eccentricity (of ellipse)	The ratio of the distance between the center and the focus of an ellipse to its semimajor axis. It is expressed by $e = \sqrt{1 - b^2/a^2}$ if a is the semimajor axis and b the semiminor axis.
Ecliptic	The great circle marking the intersection of the celestial sphere with the (mean) orbital plane of the Earth's center. Or, approximately: the annual apparent path of the Sun's center on the celestial sphere, as seen from the Earth.
Ecliptic Poles	The points of the celestial sphere which are the intersections with the line perpendicular to the ecliptic.

Elongation	The difference in geocentric (or planetocentric) longitudes between the Sun and the planet observed. A planet is in "eastern elongation" when it follows the Sun in its apparent daily motion; it is in "western elongation" when it precedes it.
Ephemeris	A table predicting the positions of celestial bodies (Sun, Moon, planets) at regular intervals of time.
Ephemeris Second	The fraction $1/31556925.9747$ of the tropical year for 1900 January 0^d 12^h ET (i. e., at the fundamental epoch). This fundamental invariable unit of time was formally adopted by the Comité International Des Poids et Mesures in 1957. Note: The fraction above was determined by the coefficient of the time variable T in Newcomb's expression for the right ascension of the fictitious mean Sun.)
Ephemeris Time	A uniform measure of time based on the invariable unit known as the ephemeris second. Ephemeris Time was established not for practical uses (it is not readily accessible like Universal Time or mean solar time) but for theoretical uses as an accurate standard in studying the laws of motion of celestial bodies.
Epoch	The initial time adopted as the instant of reference.
Equinoxes or Equinoctial Points	The (2) intersection points of the celestial equator and the ecliptic. (Definition applying to Earth case.) One point is the 'vernal equinox' (or point at which the Sun appears to cross the equator from south to north). The other point, opposite to it (or 180° from it) is the 'autumnal equinox.' These designations were chosen to indicate the beginnings of (astronomical) spring and autumn, respectively, in the northern hemisphere of Earth. (Since seasons are reversed in the southern hemisphere, it may be preferable to use the terms March equinox and September equinox.)
First Point of Aries T	The same as vernal equinox (for Earth).

Fundamental Epoch	(From which Ephemeris Time is reckoned): the epoch that Newcomb designated as 1900 January 0, Greenwich Mean Noon, but which is now properly designated as 1900 January 0, 12^h ET (Explan. Suppl., 1961). The instant to which this designation is assigned is the instant near the beginning of the calendar year AD 1900 when the geometric mean longitude of the Sun, referred to the mean equinox of date, was 279° 41' 48.04". (Explan. Suppl., 1961).
Gaussian Gravitational Constant	A fixed and exact constant $k = 0.01720209895$ serving to define the astronomical unit of distance through Kepler's Third Law. Originally used as $k^2 = G$, the Newtonian gravitational constant.
General Perturbations	In celestial mechanics, the analytical expressions (in the form of infinite series) necessary to calculate the changes or perturbations in the orbital elements as a function of time.
Greenwich Mean Time	Practically identical with Universal Time.
Greenwich Mean Noon (or GMN)	The same as 12^h UT. Note: 1900 January 0.GMN = 1900 January 0^d12^h ET Newcomb's fundamental epoch was kept when revising the UT system and establishing the ET system.
Heliocentric	Sun-centered (derived from 'helios,' the Greek word for Sun).
Hour Angle (local and Greenwich)	The angle or arc measured westward along the celestial equator from the local (or Greenwich) meridian to the hour circle of the body in question.
Hour Circle	A great circle of the celestial sphere through the celestial poles. Also called circle of right ascension.
Julian Calendar	A simple continuous calendar reckoning the number of astronomical days elapsed since a chosen ancient epoch (January 1, GMN: 4713 BC).
Julian Century	Unit of time equal to exactly 36525 days (mean solar).
Julian Date (of an event or instant)	The Julian Day Number followed by the decimal fraction of the day elapsed since preceding noon. It may be measured in days UT (Julian Date J.D.) or in days ephemeris (Julian Date J.E.D.).

Julian Day Number	The integral number of mean solar days elapsed since the chosen Julian epoch.
Julian Year	Unit of time equal to exactly 365.25 days (mean solar).
Kepler's Laws (of planetary motion)	Three laws applying to the motion of one planet around the Sun, assuming that it is not disturbed gravitationally by any other planet.
Laplacian Plane (of a satellite)	An invariable plane relative to the planet's equator, and upon which the precessing plane of a satellite's orbit maintains a (nearly) constant inclination.
Line of Apesides	The line connecting the two apses; i.e., the major axis of an elliptical orbit
Line of Nodes	The intersection line of the orbit plane and a reference plane or circle (usually either the ecliptic or an equator) on the celestial sphere.
Longitude (of a point)	Arc or angular distance along a great circle in a reference plane, counted from an adopted reference point.
Martian Vernal Equinox ($\gamma_{\oplus}$)	On an areocentric sphere, the ascending node of the orbit of Mars on its equator.
Mean Anomaly	The angle described by the radius vector of the orbiting body in the interval of time $(t-t_0)$ since perihelion passage, assuming constant mean angular motion $n = 2\pi/P$, where P is the sidereal period of revolution. It is the same as true anomaly but with a fictitious orbiting body revolving with uniform angular velocity around the Sun (or primary).
Mean Distance	Average distance of a body from its primary. Equal to the semimajor axis.
Mean Equator	The mean position of the plane of the equator as resulting from the effect of precession, but not of nutation.
Mean Equinox of Date	The ascending node of the ecliptic on the mean equator at a particular date. It is a fictitious equinox with the effect of nutation removed.

Mean Motion	The mean angular velocity of the orbiting body. It is expressed by $n = 2\pi/P$, if P is the period of revolution.
Mean Solar Day	The basic interval of time in the mean solar time system; i.e., the interval between two consecutive transits of the fictitious mean sun over a meridian (corrected for the motion of the pole).
Mean Solar Second	The fraction $1/86400$ of the mean solar day. (The mean solar second was the fundamental unit of time before the adoption of the ephemeris second in 1957.)
Mean Solar Time (for Earth)	(At any place) the local hour angle of the fictitious mean sun plus 12 hours (to start from midnight).
Mean Sun (for Earth)	A fictitious sun moving eastward along the celestial equator at a uniform rate such that it completes a revolution in the same time as that of the actual Sun along the ecliptic.
Meridian Transit	The passage of a celestial body across a celestial meridian.
Nadir	The point of the celestial sphere exactly opposite (180°) from the zenith.
Nutation	The somewhat irregular circular motion of the true pole of a planet's equator about the mean pole. For Earth, the nutation period is of 18.6 years, while its angular amplitude (constant of nutation) is of 9.210 arc sec. For Mars, it is still not known but appears to be even smaller. Nutation is essentially the short-period periodic portion of the precessional motion of the pole and depends principally (in the case of the Earth) on the periodic motion of the Moon with small contributions from the Sun and other planets.
Obliquity of the Ecliptic	The angle between the planes of the celestial equator and of the ecliptic.
Opposition	Time when the apparent geocentric (planetocentric) longitudes of another planet and the Sun differ by exactly 180° .
Orbit	The path of a celestial body under the gravitational attraction of another body or bodies.
Pericenter	The point on an orbit that is nearest to the center of attraction.

Perifocus	Same as pericenter.
Perihelion	The point on a heliocentric orbit that is closest to the Sun.
Periodic Perturbations	Perturbations which are of short period compared to secular perturbations.
Perturbations (of an orbit)	Deviations from Keplerian or true elliptical orbital motion around the Sun or primary.
Precession (of the equinoxes of a planet)	The very slow conical motion of the rotational axis of a planet about the normal to its orbital plane, as caused by the attraction of the Sun, the other planets, and especially any large satellite upon the equatorial bulge of the planet. (Precession is commonly exhibited by a spinning top under the torque produced by gravity.)
Quadrature	The position of a planet (or Moon) at 90° to the Sun as measured from the center of the Earth.
Retrograde Sense	The opposite of direct sense of rotation or revolution; that is clockwise as seen from the north pole.
Revolution	The orbital motion of a celestial body (planet or satellite) around another more massive body (Sun or primary).
Right Ascension	The arc along the celestial equator measured eastward from the vernal equinox to the hour circle of the body, from 0 to 24 hours or 0° to 360°. Note: Right ascension and declination of a body are its celestial coordinates in the 'equatorial' system.
Rotation	The spinning of a celestial body (Sun, planet or satellite) about an axis passing through it.
Secular Perturbations	Perturbations which are very slowly changing the orbit of a planet (or satellite). It was shown by Laplace and Lagrange that such perturbations actually are periodic with extremely long periods.
Semimajor Axis (of ellipse)	One-half the longest diameter of an ellipse. Also called "mean distance."

Semiminor Axis (of ellipse)	One-half the shortest diameter of an ellipse.
Sidereal	With reference to the stars.
Solstices or Solsticial Points	The (2) points on the ecliptic (Earth case) which are 90° from the equinoxes. One is the summer solstice, the other the winter solstice.
Special Perturbations	In celestial mechanics, the perturbations in the orbital elements at successive time intervals as calculated through a stepwise numerical integration of the equations of motion.
Superior Conjunction	Time when the apparent geocentric (planetocentric) longitudes of another planet and the Sun are exactly the same, with the Sun between the two planets (except for latitude differences).
Synodic Period (of revolution of two planets or satellites)	The time interval between two successive heliocentric or planetocentric conjunctions in longitude.
Tropical Year	The interval between two successive returns of the (fictitious mean) Sun to the (mean) vernal equinox. Or: the interval during which the Sun's mean longitude (or right ascension), referred to the mean vernal equinox, increases by 360° (Explan. Suppl., 1961).
True Anomaly	The angle described by the radius vector from the Sun (or primary) to the planet (or satellite) counted from perihelion (or perifocus) position in the direction of motion.
True Equinox of Date	The intersection of the true equator (as affected by both precession and nutation) with the true ecliptic.
Universal Time	The mean solar time referred to the Greenwich meridian.
Vernal Equinox (Υ)	The ascending node of the ecliptic on the equator.
Zenith (astronomical)	The point of the celestial sphere directly (vertically) above the observer.

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2. INTERIOR

DATA SUMMARY

Gravitational Coefficient J_2	0.00195	(Wilkins, 1967; Cain, 1967)
Flattening:		
Dynamical (preferred value) f_d	0.00525	(Cain, 1967)
Optical f_o	0.012	(de Vaucouleurs, 1964)
Polar moment of inertia factor (hydrostatic) C/MR_{eq}^2	0.377	
Interior models	See Figs. 1 and 2, etc.	

DISCUSSION

2.1 The Theory of a Rotating Planet

Flattening

The flattening of a planet is the difference between the equatorial and polar radii divided by the equatorial radius. (For a more detailed description, see MacDonald, 1962.)

Geometric Relationships

Any rotating, self-gravitating, fluid body will assume a shape such that its surface is everywhere normal to the resultant of gravity and centrifugal force (Sterne, 1960). This equipotential surface will approximate a spheroid for slow rotation (the case for planets) (Jardetzky, 1958). Real bodies may have sufficient strength in their mantles to allow their surfaces to depart somewhat from an equipotential surface or to support internal inhomogeneities.

The simple geometric relationships for a spheroid of revolution about an axis are given below, where

- f = flattening
- e = eccentricity
- R = radius at geocentric latitude ϕ
- R_{eq} = equatorial radius
- R_p = polar radius
- R_m = mean radius

By definition

$$f = \frac{R_{eq} - R_p}{R_{eq}} = 1 - \frac{R_p}{R_{eq}}$$

and

$$e = \frac{\left(R_{eq}^2 - R_p^2\right)^{1/2}}{R_{eq}} = \left(1 - \frac{R_p^2}{R_{eq}^2}\right)^{1/2}$$

Thus

$$e^2 = f(2 - f)$$

and

$$f \equiv 1 - \sqrt{1 - e^2}$$

or, ignoring $O(f^2)$,

$$f \approx \frac{e^2}{2}$$

At any planetocentric latitude ϕ

$$R \equiv R_{eq} \left(\frac{1 - e^2}{1 - e^2 \cos^2 \phi} \right)^{1/2}$$

or, ignoring $O(f^2)$,

$$R \approx R_{eq} (1 - f \sin^2 \phi)$$

and mean radius

$$R_m = R_{eq} \left(1 - \frac{f}{2} \right)$$

Dynamical Flattening

Dynamical flattening is a flattening given by the gravity potential of a primary body; the equipotential surfaces described by this potential may or may not refer to the material surface of that body. The dynamical flattening of Mars

is derived from consideration of the orbital perturbations of Phobos and Deimos. The theory of this motion, with improved data from Mariner 4, yields a value of $f_d = 0.00525 \pm 0.00001$ (Cain, 1967). A quantitative discussion of these ideas is given in paragraphs beginning on page 4.

The dynamical flattening of Mars is well determined and corresponds to a value theoretically reasonable for a planet with a very small amount of compression toward its center. Spectroscopic measurements agree with this value. Spectroscopic determinations also show no more CO_2 at the polar caps than at the equator. If the true surface were that implied by the optical flattening value, CO_2 pressure at the caps should be several times that at the equator (Hanselman, 1965). The figure as determined by Mariners 4, 6, and 7 agrees nicely with the dynamical value (see Sections 1 and 5.2). For these reasons the mean surface of Mars is suggested to be nearly that indicated by the dynamical flattening.

Optical Flattening

Optical flattening of the apparent planetary surface is measured either directly on the optical image with a micrometer or heliometer, or indirectly using photographic images or photoelectric scans. Most results are between 0.010 and 0.015, with recent values near 0.012, apparently corresponding to a surface far from an equipotential. However, optical flattening determinations are far less accurate than those obtained for dynamical flattening. Optical measurements are difficult to make and are subject to many sources of systematic error and personal evaluation, for the following reasons:

- 1) Obscuration, by the Martian atmosphere, of the planetary surface (edge of the disk).
- 2) Turbulence in the Earth's atmosphere.
- 3) Preferential placement of crosswire relative to a bright or dark area.
- 4) The gibbous nature of the Martian disk; noncircularity of the disk due to phase angle and oblateness of the planet.
- 5) Possible exaggerated equatorial diameter measurements caused by dust particles in the atmosphere during the perihelic oppositions when such measurements are characteristically made.
- 6) Mars seldom exhibits a true polar diameter because of axial tilt.
- 7) Photographic images also lack sharpness at image edge.
- 8) Photoelectric scans suffer from finite slit width, instrumental scattering, and orientation problems.

External Gravitational Potential (of a spheroid)

It is well known that the external gravitational potential $V(r, \phi, \lambda)$, of a planet is given by an expansion in terms of "spherical harmonics," which are functions of latitude ϕ and longitude λ ; (see Jeffreys, 1970). If the planet is axially (i. e., rotationally) symmetric (a spheroid), the spherical harmonics reduce to "zonal" harmonics, which are functions of latitude ϕ only (through Legendre polynomials $P_i(\sin \phi)$). In its simplest form, the potential V at a point (r, ϕ) external to such a planetary body is given (keeping only the two first terms) by

$$V = -\frac{GM}{r} + \frac{GM}{2r^3} R_{eq}^2 \cdot J_2 (3 \sin^2 \phi - 1)$$

where (r, ϕ) are the planetocentric coordinates of distance and latitude of the point:

G = the absolute gravitational constant

M = the mass of the planet

R_{eq} = its equatorial radius

J_2 = a dimensionless coefficient (to be determined)

This coefficient J_2 of the second harmonic is the most important in defining the shape or figure of the planetary body (or rather its approximating equipotential spheroid). If higher harmonics were considered, their coefficients ($J_4, \dots$), which are much smaller, would describe the deviations of the actual equipotential surface from the spheroid.

It can be shown theoretically that coefficient J_2 is related to the difference between the principal moments of inertia C (about the polar axis) and A (about an equatorial axis) of the body by an important relation independent of internal structure:

$$J_2 = \frac{C - A}{MR_{eq}^2}$$

These coefficients J_2, J_4 , etc. may be measured observationally with great precision from study of the orbital motions (perturbations) of close satellites and orbiters (such as planned for Mariner 9). From Earth, observations of the Martian satellites Phobos and Deimos are accurate enough to yield a reliable value of J_2 , but not J_4 . It is also possible to obtain J_2 from perturbations of a flyby trajectory.

Potential of Gravity (at surface)

The potential of gravity at any point on the surface of the approximating equipotential of the body is the sum of gravitational potential and rotational potential (due to centripetal acceleration):

$$U = V - \frac{\omega^2}{2} r^2 \cos^2 \phi$$

where ω is the angular rate of rotation of planet, and (r, ϕ) are now the coordinates of the surface point.

Note: In the case of the Earth, the surface of constant (geo) potential U , or equipotential U_0 , coinciding with the mean sea level, is by definition the so-called "geoid." This irregular geoid is approximated in (physical) geodesy by the more regular "normal spheroid" of revolution, or even by the "reference ellipsoid" of revolution (used in geometrical geodesy), which are mathematically tractable surfaces.*

From the expression for the potential of gravity U , the flattening of the approximating spheroid or ellipsoid can be derived to first order terms by

$$\frac{R_{eq} - R_p}{R_{eq}} \equiv f_d \approx \frac{3}{2} J_2 + \frac{1}{2} \cdot \frac{\omega^2 R_{eq}^2}{GM}$$

often written

$$f_d \approx \frac{3}{2} J_2 + \frac{1}{2} m$$

where

R_{eq} and R_p = the equatorial and polar radii of the spheroid or ellipsoid

m = the ratio of centrifugal to gravitational acceleration at the equator

that is

$$m = \frac{\omega^2 R_{eq}^2}{GM/R_{eq}^2}$$

*See, for example, Handbook of Geophysics and Space Environments (section Geodesy), edited by S. L. Valley, at Mc Graw-Hill, N. Y. (1966).

Using the mean density of the planet

$$\bar{\rho} = M / \frac{4}{3} \pi R_m^3$$

and its period of rotation

$$P = \frac{2\pi}{\omega}$$

this ratio is sometimes taken to be equal to

$$m = \frac{3\pi}{G\bar{\rho}P^2}$$

which is an approximation valid when flattening is small (i. e., $R_M \approx R_{eq}$).

The flattening f_d is usually referred to as the "dynamical flattening."

Determination of Coefficient J_2 From Satellite Orbital Precession

An astronomically observed value of gravitational coefficient J_2 can be deduced for a planet from the period of precession of the orbital pole (or line of nodes) of a close satellite's motion, when perturbed by the planet's oblateness:

$$J_2 \approx \frac{2 a^2 p}{3 R_{eq}^2 \omega}$$

where

a = semi-major axis of satellite orbit

p = period of revolution of satellite

R_{eq} = equatorial radius of planet

ω = period of precession of satellite orbit

The estimate of J_2 does not depend on the value of mass M nor on any assumption on the internal mass distribution of the planet.

The value of $J_2 R_{eq}^2$ obtained from the best available satellite orbital data is:

$$J_2 R_{eq}^2 = (1.013 \pm 0.003) \times 10^{-12} \text{ AU}^2 \quad (\text{Wilkins, 1967})$$

Using this value and the equatorial radius $R_{eq} = 3393.4$ km obtained from Mariner 4 data, Cain derived the coefficient $J_2 = 0.00195 \pm 0.00002$ (Cain, 1967).*

Determination of the (Polar) Moment of Inertia

The moment of inertia of a planet can only be determined from measurements made externally to its surface (and not from gravity measurements at its surface). There are two well-known methods for determining the principal or polar moment C:

- 1) Method A utilizes the "mechanical ellipticity" of the planet, a quantity defined by $H = (C-A)/C$, and the coefficient

$$J_2 = \frac{(C-A)}{MR_{eq}^2}$$

Indeed, their ratio

$$\frac{J_2}{H} = \frac{C}{MR_{eq}^2}$$

yields C immediately.

This method works well for Earth, because H is well determined from the rate of precession of its axis of rotation, resulting from the torques exerted upon it by the Moon and the Sun. In the case of Mars, the mechanical ellipticity H is not well determined. Because the tiny satellites do not exert a significant torque, and the Sun produces very little torque, H can only be approximated from an assumed internal density distribution, which is unsatisfactory. (See, for example, Lowell's 1914 estimate: $H \approx 0.005$). Hopefully, in the near future, H will be determined by spacecraft.

- 2) Method B combines the observed coefficient J_2 , or equivalently the dynamical flattening

$$f_d \approx \frac{3}{2} J_2 + \frac{1}{2} m$$

*This value of J_2 may be compared with that obtained by Null (1971) from the perturbations of Mariner 4 flyby trajectory: $J_2 = 0.00187 \pm 0.00007$. Thus, $J_2 = 0.0019$. A more final value of J_2 (at least to the third significant digit) should be easily obtainable by the Mariner 9 orbiter. It was practically impossible to derive a reliable value of J_2 from the Mariners 6 and 7 flyby trajectories perturbations because of additional, nongravitational forces (N_2 gas leaks from IRS experiment, etc.), during encounter.

and the Radau-Darwin relation, which assumes hydrostatic equilibrium; that is

$$f_d \approx f_h$$

Indeed, this Radau approximation relates

$$\frac{C}{MR_{eq}^2}, \quad m \text{ and } f_h (\approx f_d)$$

This method has been applied to Mars to yield an approximate value of

$$\frac{C}{MR_{eq}^2} = 0.377$$

using the Mariner 4 data for M and R_{eq} (which both enter in m also), or

$$C = 2.79 \times 10^{43} \text{ g-cm}^2$$

By substituting this result for C into

$$\frac{(C-A)}{MR_{eq}^2} = J_2$$

one may also obtain an approximate value of the equatorial moment A .

Gravity Relation (Clairaut's Formula)

Gravity or gravitational acceleration at the surface of the planet, approximated by the equipotential ellipsoid, is normal to this ellipsoid and of a magnitude given by the gradient of the (total) potential:

$$g = - \text{grad } U$$

From the expression for U , one obtains gravity at the equator (where $r = R_{eq}$ and $\phi = 0$):

$$g_e = \frac{GM}{R_{eq}^2} \left(1 + f_d - \frac{3}{2} m \right)$$

The gravity at any other latitude ϕ is given in terms of g_e (to the accuracy of the first power of f_d) by Clairaut's formula:

$$g = g_e \left[1 + \left(\frac{5}{2} m - f_d \right) \sin^2 \phi \right]$$

(Note: Planetographic latitude ϕ' may be used instead of planetocentric latitude ϕ , with negligible loss in accuracy.)

Again, Clairaut's formula, based on f_d or J_2 , is also independent of any assumption on the internal structure of the planet (such as hydrostatic equilibrium).

Hydrostatic Flattening (Radau's Approximation)

The shape or figure of equilibrium of a rotating fluid planet, where density distributes itself in concentric layers, is provided by the solution to Clairaut's equation (see Jeffreys, 1970). This is well expressed for our purposes by the hydrostatic flattening approximation (neglecting terms of order f^2):

$$f_h = \frac{5m}{2} \left[1 + \left(\frac{5}{2} - \frac{15}{4} \cdot \frac{C}{MR_{eq}^2} \right)^2 \right]^{-1}$$

This relation between hydrostatic flattening f_h , ratio m , mass M , equatorial radius R_{eq} , and principal moment of inertia C is known as the Radau-Darwin approximation. It is often written:

$$\frac{C}{MR_{eq}^2} = \frac{2}{3} \left[1 - \frac{2}{5} \sqrt{\frac{5}{2} \cdot \frac{m}{f_h} - 1} \right]$$

If an observed or true C/MR_{eq}^2 value were available for Mars (such as given by J_2/H method), one could determine a hydrostatic flattening f_h and compare it to the dynamical flattening f_d .

A hydrostatic J_2 can be derived from f_h by substitution in the J_2 expression in f_d . Comparison of this hydrostatic J_2 with the observed J_2 may reveal a difference. This difference would indicate the extent of deviation of the actual planet from the ideal (hydrostatic) planet. This would provide evidence on the anelasticity of the planet's interior, and give an idea of the magnitude of the stress differences supported by a portion of (the mantle) or possibly the whole body (in the case of a small planet like Mars). (Note: Such stresses are likely to arise during the thermal history of the planet.)

2.2 Density Models

Introduction

At the present time, and until new measurements are secured by orbiters and/or landers, the internal structure of Mars can only be inferred from the

very few available planetary constants (the so-called "observables"). These available constants are the mass, the radii, or simply the mean radius, and the polar (or mean) moment of inertia.* The Mariner 4 flyby provided a very accurate value for the mass and a reasonable value for the moment of inertia. The three Mariner flybys established an accurate value for the equatorial radius. However, the polar radius and geometrical flattening are still not accurately known.

The two basic assumptions underlying all internal models of Mars have been: (1) analogy with the Earth, either in structure or composition; and (2) hydrostatic equilibrium. Other assumptions usually pertain to the possible discontinuities; that is, either changes of state (under increasing pressure or temperature) or composition, and the equations of state (relating pressure p to density ρ)** to adopt for each layer (crust, mantle, core).

Use is made of experimental and theoretical information obtained for the Earth, from both geophysics (seismic studies, high-pressure physics, etc.) and geochemistry (composition of rocks, ...), and data from meteoritics.

The general method for constructing an internal density distribution model for a planet is to integrate the hydrostatic equation inward, using the assumed equations of state for each layer, and attempt, by varying the thickness of each, to approximately satisfy the boundary conditions of mass, radius, and moment of inertia. The planet is generally assumed spherical in shape, except for the utilization of dynamical flattening or coefficient J_2 to derive the moment of inertia. The product of the calculations, the model(s), is therefore a density (ρ) versus radial depth (r) distribution, or a density profile $\rho(r)$ of the planet's interior.

Historical Density Models

Prior to late 1965, the exact value of the radius was still unknown. Investigators who used lower values of radius (as low as 3310 km) concluded that Mars was nearly homogeneous (i. e., without a chemically distinct core of appreciable size), such as the models of Urey (1952), MacDonald (1962), and Kovach and Anderson (1965).

Investigators who used the higher values of radius (as high as 3423 km) concluded that Mars was chemically differentiated and composed of an iron-rich (Fe-Si-Ni) core similar to Earth's, but smaller. Chemically differentiated models were produced by Jeffreys (1937), Bullen (1949), and Kozlovskaya (1966). A special or "hybrid" type of model, chemically homogeneous, but

*The polar moment of inertia is derivable from the observed coefficient J_2 , or equivalently the dynamical flattening f_d and the rotation rate ω , by means of Radau's relation assuming hydrostatic equilibrium.

**Other mechanical parameters related to density ρ (or pressure p) are also involved, namely, the (adiabatic) incompressibility k , and the rigidity μ . All these parameters depend, of course, on temperature and chemical composition. Finally, the gravity intensity g , dependent on depth r , has to be taken into account.

physically differentiated into core and mantle (with the core a dense high-pressure phase of the same silicates constituting the mantle), was ingeniously conceived by Ramsey (1948) and worked out by Lyttleton (1963).

These models are very briefly reviewed by category.

Homogeneous Models

Urey (1952) argued, by comparing the terrestrial planets, that Mars must be roughly homogeneous (or at least much less differentiated than Earth), consisting of a mixture of iron and silicate phases uniformly dispersed. He estimated from a density pressure relationship that Mars must contain about 30% iron phase.

MacDonald (1962) calculated numerous possible models of Mars' interior by varying the structural assumptions of radius, flattening, and mantle phase changes. He showed that core radius and surface density depend critically upon the value of (hydrostatic) flattening and on planet radius. Thus, a slight decrease in flattening leads to a considerable increase of core radius (and mass); while a small decrease in planet radius leads to unduly large surface densities. Adopting a mean radius of 3345 km and a flattening of 0.0050 for Mars, MacDonald finally proposed two alternative models, which are both core models. The first, MI, is a small core model, where its mass amounts to about 1% of total planetary mass and radius is about 700 km, and was derived by assuming for the mantle a phase transition creating an abrupt discontinuity in its overall (mantle) density distribution. The second model, MII, is a larger core model, where core mass is about 10% (exactly, 9.3%) of total mass and its radius about 1250 km; but it has no phase transition assumption for the mantle. The surface densities obtained were quite high, from 3.5 to 3.8 g cm⁻³. The metallic core, composed mostly of Fe and Si, has a (compressed) density of 9 g cm⁻³. MacDonald favored the small core model, MI. Both models are shown in Fig. 1.

Kovach and Anderson (1965), starting from the chemically differentiated Earth (iron-rich core and silicate mantle) as a model, investigated various Mars models, in which core and mantle material were mixed in assigned proportions. They were able to obtain a common overall (planetary) composition only by utilizing a very low value (3310 km) for the Mars' radius. Thus, they concluded that with the hypothesis of chemical differentiation, it is impossible to have a Mars similar to Earth in overall chemical composition, if its radius is much greater than 3310 km.

Chemically Differentiated Models

Jeffreys (1937), who did the initial work on interiors of terrestrial planets, actually proposed two models for Mars, illustrated in Fig. 1. One model, JI, resembled the Earth with three layers, while the other, JII, had only two layers, and no metallic core. Jeffreys preferred the first model, JI.

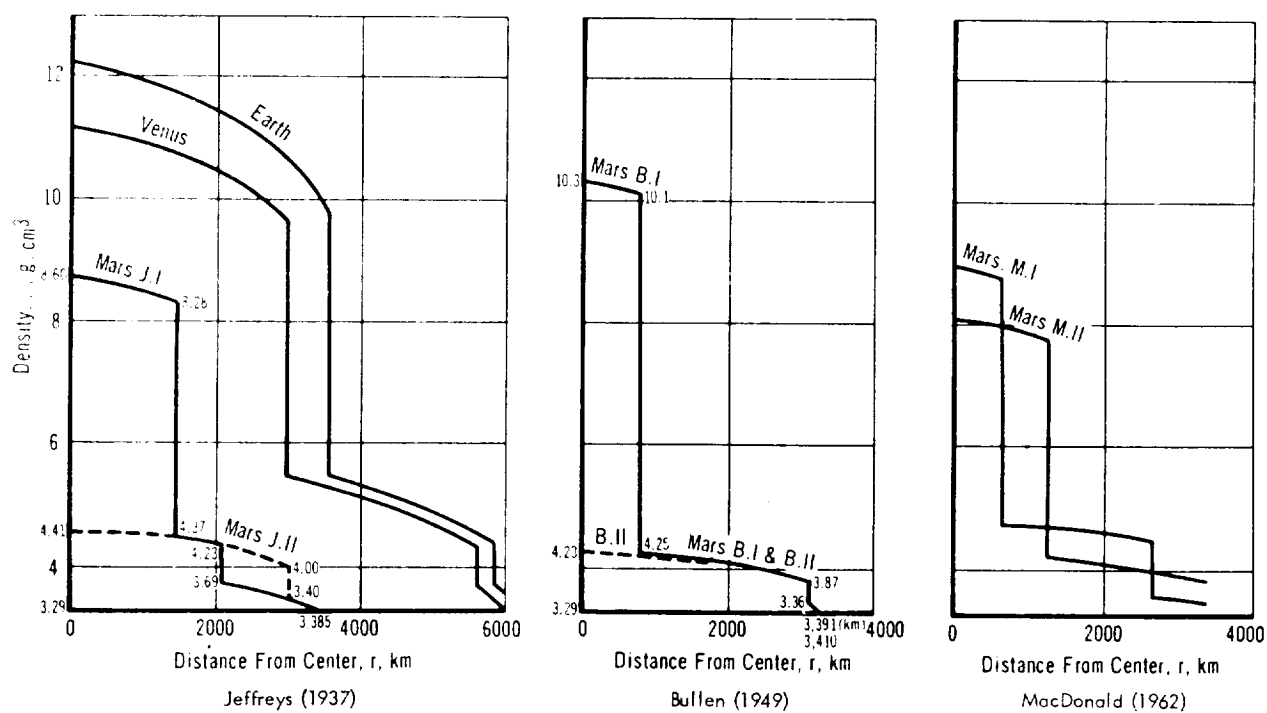


Fig. 1(a). Density models of Mars' interior

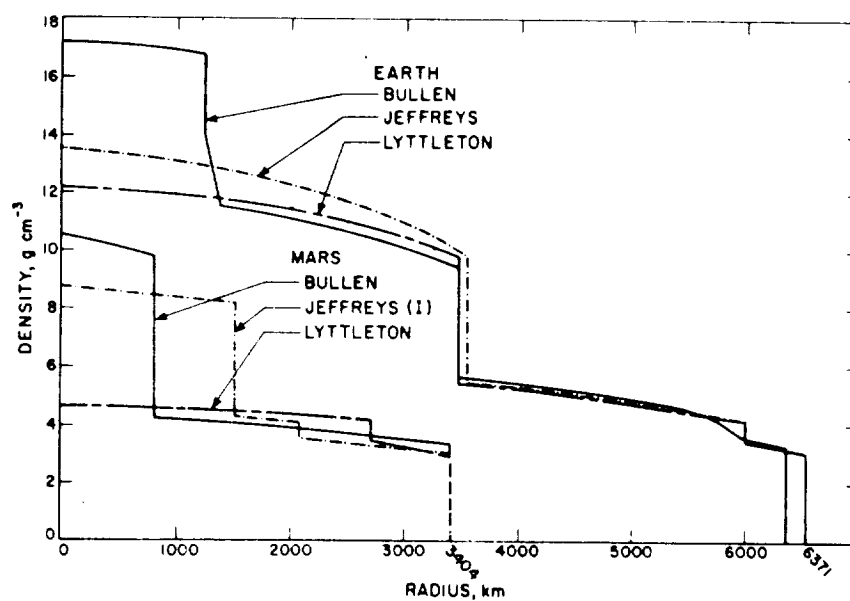


Fig. 1(b). Theoretical interior density profiles for Earth and Mars. (Jeffreys, 1937, Bullen, 1949, Lyttleton, 1963).

Bullen (1949) also calculated two models. One model, BI, with a differentiated Fe-Ni core, and the other model, BII, which was a modification of Ramsey's Earth model by using a quadratic law of incompressibility (k) versus pressure (p), instead of the usual linear law. Bullen preferred the first model, BI. See Fig. 1.

Kozlovskaya (1966) also (like many others up to Kovach and Anderson, 1965) attempted to prove the hypothesis of a common overall chemical composition for the terrestrial planets (Mars, Venus, and Earth). Starting with an Earth model of the "hybrid" type (following Ramsey, with a core of silicates in metallic state), he found that Mars on the whole must be somewhat denser than Earth. "Mars material" could be obtained by adding 5 to 8% iron to Earth material.

Hybrid Models

Ramsey (1948), at Jeffreys' suggestion, undertook the investigation of a two-layer (or two-zone) model with identical chemical (silicates) composition throughout, but with differentiation into a core of silicates in a high-pressure "metallic" state and a mantle of the same silicates in their normal (low-pressure) molecular state. The calculations to confirm his model were not completed. Ramsey's intent was to explore the broader hypothesis that all four terrestrial planets were of the same basic (silicate) composition.

Lyttleton (1963 and 1965 a, b) calculated a series of two-zone models of Mars, from the known mass, on the hypothesis that its composition is similar to that of the Earth, with the interior zone representing a phase-change produced by both pressure and temperature effects, thereby extending the Ramsey hypothesis. Because of the much lower central pressure in Mars, which on almost any model must be less than 0.3×10^{12} dyn cm⁻² (about 1/10 that for the Earth), Mars can consist of two zones only — an inner one of solid material in the same high-pressure phase as the present mantle of the Earth (below 413-km depth), and an outer one of solid material in the same form as the present outer shell of the Earth (above 413-km depth). According to this theory, Mars would be entirely solid without a liquid metallic core. Consequently, despite the closely similar angular velocity and obliquity of Mars and Earth, this theory predicted the absence of any main Martian magnetic field. This prediction was subsequently confirmed by Mariner 4 data obtained in July 1965.

The internal temperature is regarded as arising from release of radioactively produced energy, and, because of its somewhat smaller size, Mars might be expected to be at slightly lower temperatures (at comparable depths) than in the Earth. The pressure at which the phase-change (corresponding to the 20-degree discontinuity in the Earth) occurs is known to be highly sensitive to temperature (Ringwood, 1962). For this reason, the interface-pressure in Mars is not at present precisely determinable. If the interface pressure were known, a unique structure for the planet would emerge solely from the mass. To comply with the "best" observed radius — 3933 km (given by Mariner 4, 6, and 7) — the interface pressure would be about 0.07×10^{12} dyn cm⁻² (compared with 0.14×10^{12} dyn cm⁻² in the Earth), and the resulting structure would have about 60% of the total mass in the central region in mantle form

and 40% in the outer shell, with the interface occurring at a depth of about 560 km. This configuration is also consistent (within the limits of error) with the dynamical flattening derived from the satellite motions. However, closer limits to the value of this quantity and to the radius would supply a more stringent test of the theory.

The theory further suggests that with rising internal temperature (with radioactive energy release), the depth-level of the phase-discontinuity will increase to provide the requisite higher pressure, and, as a result, the planet will have undergone slight expansion, which may still be occurring. The amount of expansion is uncertain but could well be of the order of 10 km in radius during the life of the planet, with a consequent increase of surface area in the order of 10^6 km². This might well result in rifting of the extreme outer layers of Mars, although this might be disguised by effects of subsequent (long-term) surface modifications by weathering and erosion processes.

Recent Density Models

Binder's (1969) Models

The upper mantle of the Earth is currently considered to be composed of olivine [= chrysolite (a synonym), or peridot (the gem variety of olivine)], represented by the mineral series $(\text{Mg}, \text{Fe})_2\text{SiO}_4$.

Olivine is a solid solution of forsterite (pure Mg_2SiO_4) and fayalite (pure Fe_2SiO_4). The composition of olivine, which therefore may vary between these two extremes, is usually represented as mole percent of these extreme constituents abbreviated as Fo and Fa. Thus, for example, Fo₈₀ denotes olivine composed of 80% forsterite and 20% fayalite.

Recent findings on the composition and structure of the Earth's upper mantle by Anderson (1967) have shown that

- 1) There are actually two (and not one) density discontinuities, beginning at depths of 365 and 620 km, which can be correlated with changes in the packing of olivine to a spinel and then a post-spinel structure. These packing transitions (and sudden increases in density) are dependent on pressure, temperature, and the Fo/Fa ratio.
- 2) The composition of the mantle slowly changes from Fo₈₀ near the surface to Fo₆₀ at about 700 km, below which depth it apparently remains constant. This finding has been substantiated by Press (1968).

These compositional and structural data on the terrestrial mantle were applied directly to the Martian mantle in the models of Mars' interior constructed by Binder (1969). Therefore, the mantle of Mars was assumed by Binder to have three possible regions (olivine region, spinel region, and post-spinel region), each of constant composition characterized by the Fo/Fa ratio (decreasing or stationary at the discontinuity). The mantle was also assumed

to be "pure, or nearly pure, silicates and that all the free iron or iron-nickel has been differentiated into a nearly silica-free core" (Binder, 1969). The Fe-Ni core material equation of state (pressure-density function $\rho = f(p)$, where the incompressibility k enters) was derived from data on the density of Earth's core (Jacobs, 1963), allowing a 3% decrease in density to account for a solid rather than liquid Martian core. Finally, the Martian crust was assumed to have a density (2.8 g cm^{-3}) and thickness (20 km) similar to the Earth's crust.

Important constraints imposed on the models were

- 1) Internal (core) temperature limits of 700° and 1500°C . The lower limit is derived from lunar analogy. The insignificant magnetic field results (Ness et al., 1967) are taken as evidence that the Moon's interior is not above 700°C . The upper limit is derived from the assumption that lack of an appreciable magnetic field for Mars implies the lack of a fluid-conducting core, and therefore a temperature of its postulated Fe or Fe-Ni core below the melting point of these metals (Fe mp: 1550°C uncompressed).
- 2) Accurate modern values of the Mars radius ($R_{\text{eq}} = 3394 \pm 5 \text{ km}$) and dynamical flattening ($f_d = 0.00525$ given by Cain, 1967), both provided by the Mariner 4 flyby. These also yield a moment of inertia factor C/MR^2 of 0.377 ± 0.002 , if the Mariner 4 mass of Mars ($M = 6.423 \cdot 10^{26} \text{ g}$) is used.

Binder's computational model results for Mars are shown in Fig. 2. The mantle compositions varying between Fo_{60} and Fo_{70} are similar to those of Earth's mantle (averaging Fo_{65}). However, their structure is somewhat different, with the phase transitions occurring at different depths than those for Earth.* Binder also evolved another model where the mantle composition is intermediate between Earth's and meteoritic olivine. These models have a metallic (Fe, or Fe-Ni) solid core of compressed density about 8.5 g cm^{-3} , and a radius ranging from 790 to 950 km, for the most probable models, thus representing a fractional planetary mass ranging from 2.7 to 4.9%. (Note: The actual range for all models was core radius 680 to 1050 km, and core fractional mass 1.7 to 6.3%.)

Anderson's (1972) Models

Anderson (1972) reconsidered the question of differentiation for Mars after the Mariner 4 data on mass and radius were fully confirmed by Mariners 6 and 7. Although the Binder (1969) models, based on the Mariner 4 data, had indicated the likelihood of a sizable metallic (Fe-Si-Ni) core, the thermal history models of Anderson and Phinney (1967) and Hanks and Anderson (1969) seemed to thermally restrict the development of such a core which requires high melting points (of Fe, Si, Ni alloys) to be reached at some time. The requirement (taken as a constraint) of a lower melting point material for the Martian core than the usual Fe-Si-Ni mixture (assumed for cores of all terrestrial planets) can be satisfied by replacing the light element Si with sulfur,

*Because of the slower increase in pressure with depth for Mars.

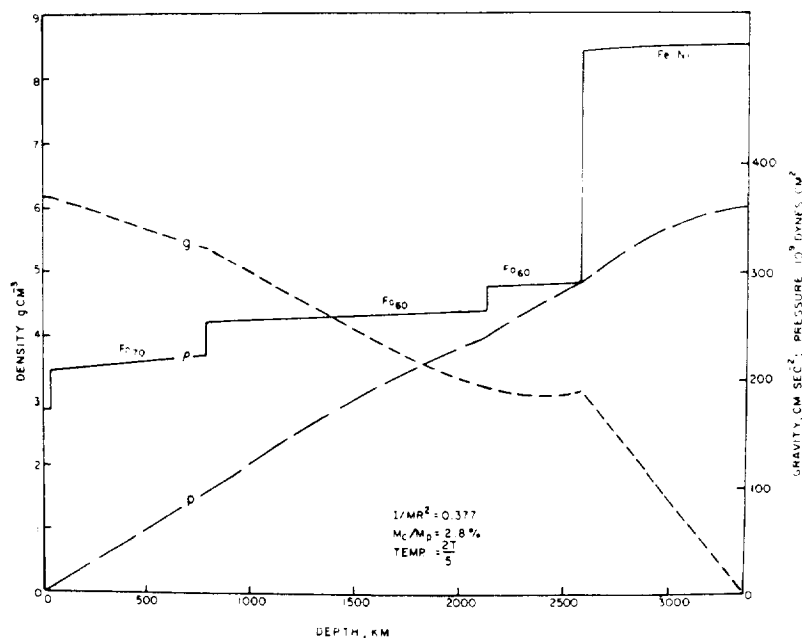


Fig. 2(a). Density (ρ), gravity (g), and pressure (p) profiles of a model representative of the models that satisfy the moment of inertia and temperature limits and that have mantle composition similar to the composition of the mantle of the Earth (Binder, 1969).

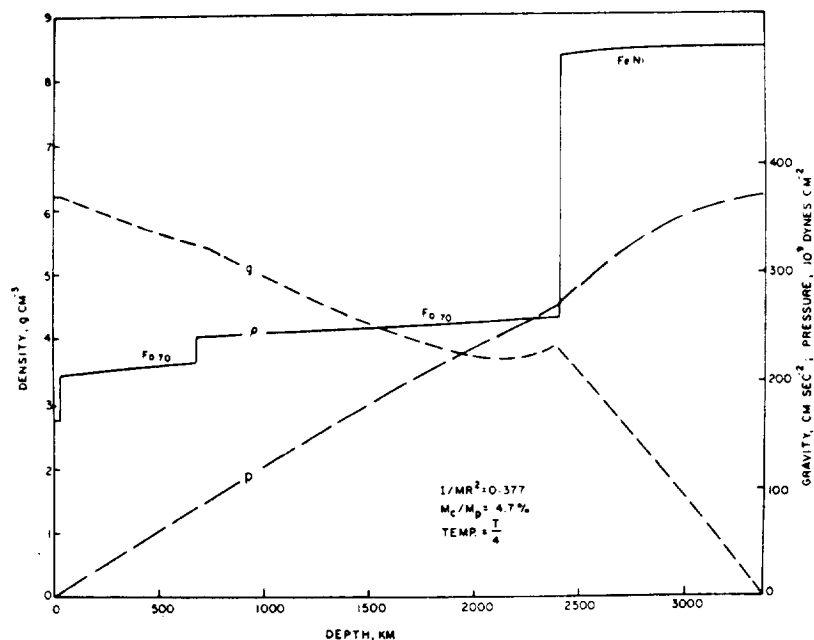


Fig. 2(b). Density (ρ), gravity (g), and pressure (p) profiles of a model representative of the models that satisfy the moment of inertia and temperature limits and that have a mantle composition intermediate between the composition of the terrestrial mantle and the composition of olivine in meteorites (Binder, 1969).

which is cosmically abundant yet produces an alloy (Fe-S-Ni) that melts at a lower temperature. The possibility of sulfur as a major element in the core has been discussed for the Earth by Murthy and Hall (1970), and for both Earth and Mars by Anderson et al. (1971), who concluded that sulfur should be abundant in the core of small, relatively cold planets like Mars.* An examination of the binary phase diagram for the system Fe-FeS (see Fig. 3) indicates that the eutectic Fe-FeS melts at a low temperature, near 990°C, and is relatively insensitive to pressure, according to the Brett and Bell (1969) experiments up to 30 kb. Thus, by assuming an FeS or S rich meteoritic (chondritic) composition for Mars initially, a core can start forming at temperatures exceeding this low eutectic temperature. However, core formation cannot proceed to completion (total differentiation), or nearly so, unless most of the planet's interior exceeds the liquidus temperature for some time.

On this basis, Anderson (1972) constructed meteoritic (chondritic) models for Mars interior; two of which, in particular, gave a sizable Fe-S-Ni core-- of radius nearly half ($R_c/R \sim 0.45$) that of the planet--containing about 12% of the total mass of Mars and a mantle rich in (the remaining) Fe or FeO. The total Fe content of Mars would be about 25-28%, close to that of chondrites,** but less than Earth's 35% Fe, and this regardless of assumptions on overall composition or distribution of Fe in the Mars models. The implied FeO content of the mantle is 21-24% by mass. Thus, they concluded from their chondritic models (that these suggest) that Mars: (1) should have a smaller and lighter (less dense) core than Earth, but definitely richer in sulfur and poorer in silicon; and (2) would have a denser mantle rich in FeO or Fe (and Ni).

The details of Anderson's (1972) two main representative meteoritic models are as follows:

- 1) One model ("Model II") had the starting composition of ordinary chondrites (11.7% Fe, 1.3% Ni, 5.9% FeS; i. e., 19% potential core forming material). Upon heating, most of the sulfur (FeS) melts and settles into a core, which collects about 63% of the available potential core-forming material, while much Fe + Ni remains solid in the mantle mixed with the silicates. The resulting density of the core is 5.85 g cm^{-3} , and that of the mantle is 3.54 g cm^{-3} (at zero-pressure). This model is incompletely differentiated.
- 2) An alternative model ("Model I"), composed of a mixture of 75% carbonaceous chondrites Type III and 25% ordinary chondrites, and accommodating higher temperatures, yielded complete separation of core and mantle, which have densities of 5.78 and 3.49 g cm^{-3} , respectively. The mantle here has high FeO, from the Type III carbonaceous chondrite. The model is fully differentiated.

*The idea is not new; Murthy and Hall mention that Fish et al. (1960), and Urey (1966), had "pointed out that among the major phases in meteorites, an iron-sulfur melt would be the first to be produced on heating."

**Ordinary chondrites have 17% free Fe and 5% FeS; carbonaceous chondrites have little free Fe but 7-25% FeS.

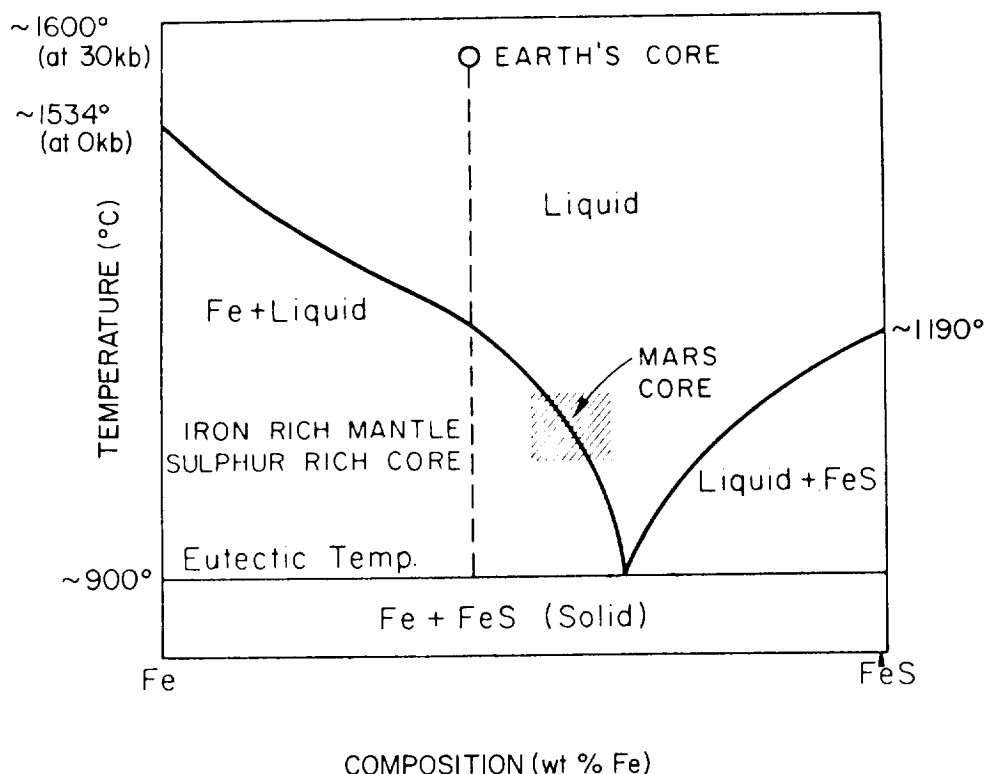


Fig. 3. Schematic binary phase diagram for the system Fe-FeS (Anderson, 1972).

Figure 4 shows a wide range of possible Mars models (not necessarily of meteoritic composition) which are consistent with the presently known values of radius R , mass M , and moment of inertia C . It can be seen that the more plausible models, those of chondritic compositions (such as Models I and II) only occupy a narrow (hachured) region in the plot of density versus fractional radius. Note that all models have about the same mantle density, while core density and size (fractional radius) have wide, inverse variations.

Implications of Anderson's (1972) Chondritic Models

Planet formation. The greater ability of Mars to retain sulfur (than Earth) would be explainable in terms of lower accretional energies and temperatures during its growth, which was probably slower than the Earth's. While the Martian core is rich in sulfur, it is poor in silicon, according to the models. High accretional temperatures and rapid solidification would be necessary for a Martian core to be rich in silicon. (See Anderson et al., 1971).

Magnetic field. The observations of a negligible magnetic field (by Mariner 4) and a rapid rotation rate for Mars have usually been interpreted as evidence against the presence of a molten iron-rich core, as in Earth, where a dynamo effect takes place generating the field. The exact mechanism driving the geomagnetic dynamo has not been ascertained yet, but recent views (e.g., Malkus, 1968) attribute the driving force to the differential precessional torque

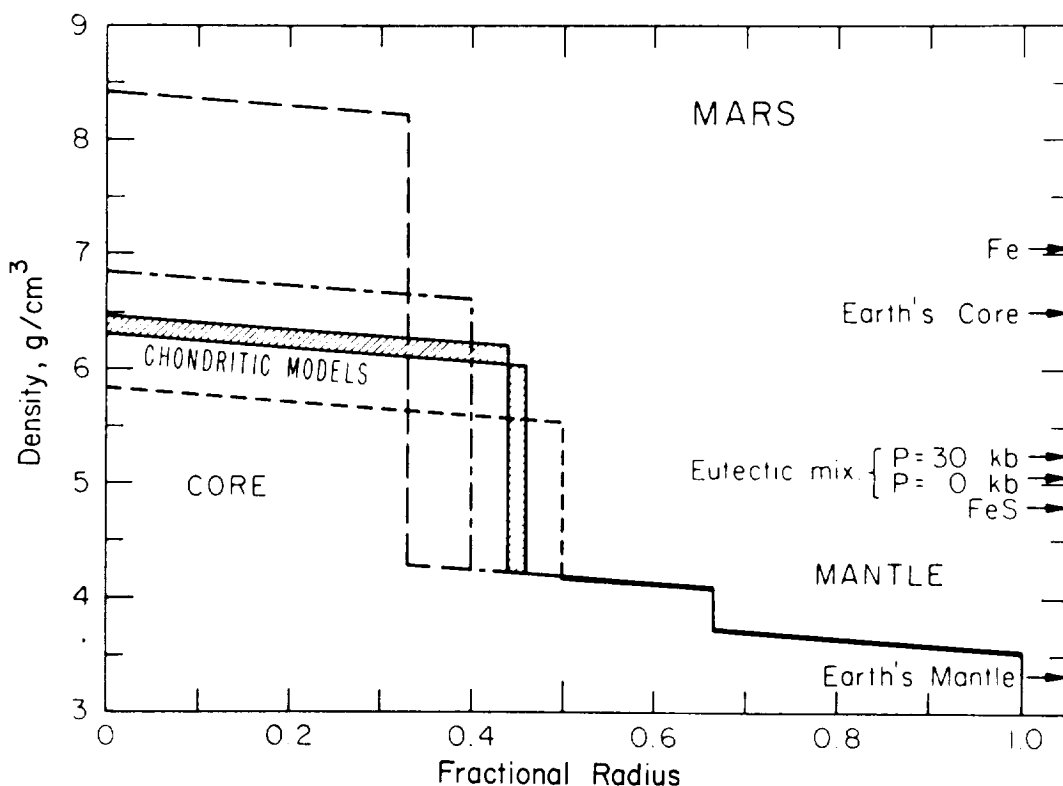


Fig. 4. Possible density models of Mars satisfying proper mean density and moment of inertia of the planet, calculated by Anderson (1972).

acted upon the Earth's core and mantle, primarily by the large, close Moon, and to a lesser extent by the Sun. In the case of Mars, because there is no large Moon, and the Sun is further away, an effective torque may not be present. Other reasons limiting the dynamo action were also advanced by Anderson (1972): the smaller size of the (proposed) Martian core, and, if sulfur is abundant, its high resistivity which would lower the magnetic Reynolds number; and, possibly, the low viscosity of the core (under lower prevailing temperatures and pressures), and the shielding effect of an iron-rich mantle. Anderson (1972) considers it is "unlikely that Mars ever had a substantial magnetic field of internal origin."

2.3 Thermal History Models

Introduction

Calculations of the thermal history of the interior of a planet can aid greatly in understanding the evolution of the whole planet, from its formation down to the present. * The study of the thermal history of the terrestrial planets

*At least they permit interesting speculations; see for example Fanale (1971).

was revived some ten years ago when accretional theories* of planet formation at relatively low temperatures had gained wide acceptance. New thermal models were constructed first for the meteorites and asteroids (Allan and Jacobs, 1956), then for the Earth (Lubimova, 1958), the Moon (Levin, 1962), and the terrestrial planets (MacDonald, 1959, 1962). The method for constructing such models has been reviewed by MacDonald (1959). Because many assumptions are required, the calculations are highly speculative. The initial conditions prevailing upon accretion, as well as the subsequent mechanisms of heat generation, all have to be prescribed from meagre data and uncertain discussions. Extending the calculations for the Earth and using conclusions derived therefrom, similar models were constructed for the other terrestrial planets. However, it was soon realized that the Earth analogy should not be carried too far, especially in the case of Mars, because of its much smaller mass. Later, to meet certain geochemical constraints, a challenging 'hot origin' theory was proposed (for the Earth especially) by Ringwood (1966) which assumes: rapid accretion followed immediately by core formation or differentiation. This 'hot origin' hypothesis was not widely accepted. Models were then developed by Anderson et al. to study the sensitive interplay of accretion and radioactive abundances upon differentiation, for both Earth and Mars. The Anderson models appear to point toward this hypothesis for Earth, and perhaps for Mars, unless a sulfurized core is assumed (Anderson, 1972).

Some Planetary History

Before reviewing thermal history models, it is instructive and helpful to briefly describe the origin and evolution of a typical Earth-like planet, as commonly understood. This evolution, it will be seen, is chiefly governed by the generation and release of thermal energies at various times, and the possibility of chemical differentiation.

It is now generally believed that most bodies of the solar system originated through the gravitational agglomeration, "accretion," of a primordial mixture of dust and gases under relatively low temperatures ($100^{\circ} - 1000^{\circ}\text{K}$) and in relatively short periods of time (1 - 100 million years). This major early accretional phase produced the so-called "protoplanets," which were still, relatively cold, undifferentiated bodies. The protoplanets' "initial" temperature was primarily dependent on the accretion rate (or total accretion time), being much higher if the rate were faster. Other lesser heat sources, besides loss of gravitational energies, also contributed to temperature; namely, adiabatic self-compression, and the decay of short-lived radioisotopes (such as I^{129} , with half-lives $< 10^8$ years). Subsequently, the temperature of the protoplanet continued to rise internally, due to the decay of long-lived radioisotopes (K^{40} , Th^{232} , U^{235} and U^{238}), and the difficulty for the generated heat to flow toward the surface and escape into space (mostly rocky material having low thermal conductivity and high opacity). After some time, the internal temperature became so great as to reach the melting point of iron (and similar

*These accretional theories were developed through the work on the origin of the solar system by such men as Urey (1952), Alfven (1954), Hoyle (1960), Cameron (1962), Fowler et al. (1962), etc.

metals), and "differentiation" began. At this point, molten iron descended by gravity toward the center of the planet to form a heavy metallic "core," while the rocky silicate material ascended to form the "mantle." This separation or core formation converted more gravitational energy into heat, accelerating the differentiation process to completion in a shorter time. This resulted in a hot, differentiated planet.

The so-called "early thermal history" of a planet commences with accretion and ends just before differentiation or the beginning of core formation. The "later thermal history" starts with core formation and covers the total differentiation stages of the planet. This evolution reflects the classical views.

Recent Thermal Models

Anderson and Phinney (1967)

Anderson and Phinney made early thermal history calculations for undifferentiated planets of the mass of Earth and Mars, starting (initially) with a surface temperature $T(0,0)$ of either 400° , 330° , or 100°K , and assuming homogeneous distribution of the long-lived radioactive elements throughout the protoplanet, with average abundances called "terrestrial"* by geophysicists (instead of the chondritic abundances previously used). The calculated profiles showed that for the case $T(0,0) = 400^\circ\text{K}$, the melting point of iron is reached at the center of both planets, some $2 \cdot 10^9$ years after accretion for the Earth, but 4.46×10^9 years after accretion (i. e., the present time) for Mars. For the case where $T(0,0) = 330^\circ\text{K}$, no melting of iron occurs for Mars (regardless of the lattice conductivity postulated), while there is still some iron melting at Earth's center. For the very low temperature $T(0,0) = 100^\circ\text{K}$, neither Mars nor Earth can reach the melting point of iron, and both remain undifferentiated. Their conclusion was that "it is fairly easy to differentiate an Earth, but difficult to differentiate a Mars" if the estimates of initial temperatures and radioactive abundances are close to true conditions.

Hanks and Anderson (1969)

Hanks and Anderson calculated early thermal histories of both Earth and Mars for comparison purposes, assuming their overall compositions and accretional histories to be roughly similar. Their main objective was to determine the early thermal conditions for Earth permitting core formation and large-scale differentiation to occur within the first 1.1 billion years following accretion, in order to antedate the oldest known terrestrial rock (3.4 billion years old). The use of Mars as a comparison planet (rather than Venus) was of

*Specifically, they took the ratios $\text{K/U} = 10^4$ and $\text{Th/U} = 3.7$, determined from terrestrial rocks by Wasserburg et al. (1964), then "calibrated" these ratios to the present U content in Earth's crust and mantle, $4.5 \times 10^{-8} \text{ g g}^{-1}$, as proposed by MacDonald (1964). Finally, they reduced the values obtained to account for dilution by mixing with the present core assumed free of radioactivity.

interest due to the fact that its mass is much smaller than Earth's, and therefore the gravitational energies released (converted to heat) upon accretion are also much smaller. In addition, since astronomical data showed Mars appeared to be nearly homogeneous or undifferentiated, it would provide a sensitive test for the hypothetical onset of differentiation (melting of iron and/or silicates) in a smaller body.

They first constructed two Mars models patterned after two Earth models, which differed in their radioactive abundances and total accretion times (t_{acc}). One model, Mars ID, composed of the usual chondritic abundances and $t_{acc} = 500,000$ years, and a second model, Mars IID, with the so-called "terrestrial" abundances (of Wasserburg et al. 1964), scaled down by MacDonald (1964) and reduced by Anderson and Phinney (1967) and $t_{acc} = 300,000$ years. The resulting thermal profiles showed that the Mars ID model produced molten iron in 2.1 billion years and the Mars IID model in 3.0 billion years after accretion, see Fig. 5. They concluded that the assumed radioactive abundances were too high for Mars, if it is still undifferentiated today. To prevent melting of iron in Mars, they then reduced the terrestrial abundances to 0.8 of their original values and proceeded to recalculate profiles for a Mars II'D model, whereby it would take 4.7 billion years after accretion to produce molten iron. See Fig. 6 (shown originally without the FeS liquidus and Fe-FeS eutectic dashed lines).

Unfortunately, at the time, the authors did not consider the alternative possibility of a differentiated Mars and further investigate the thermal conditions leading to the formation of a Martian core of lighter composition than Earth's core. Later, however, Anderson (1972), in the light of his Fe-S-Ni core model for Mars, added the dashed lines for the low-melting Fe-FeS eutectic and for the FeS liquidus data to Fig. 6, and stated that "much of the interior of Mars is between the eutectic and liquidus temperatures, which suggests partial, rather than total, melting and incomplete separation of potential core forming material." By considerably lowering the temperature necessary for core formation in Mars interior, the Anderson (1972) scheme involving sulfur also reduces the time required for the onset of differentiation — to perhaps 3×10^9 years in Mars II'D (see Fig. 6). According to Anderson (1972), the formation of a sulfurized Martian core would release only a "negligible amount of heat" (primarily because of the small mass of the planet). The differentiation process would then be much slower than for the Earth.

The thermal models presented above implicitly presuppose homogeneous accretion; i. e., accretion of primordial matter into an essentially homogeneous protoplanet with differentiation subsequently taking place. Recently, a new class of models was proposed by Turekian and Clark (1969), based upon inhomogeneous accretion. As the primitive nebula cooled down, successive condensations of elements and components (in roughly the order of increasing vapor pressure and decreasing density) formed the protoplanet presumed to be initially layered with a central core of Fe and Ni. Such a model has in fact been presented for the Earth by Clark, Turekian, and Grossman (1972), and also for the Moon by Hanks and Anderson (Hanks, 1972). The application of the inhomogeneous accretion concept to Mars would produce direct core formation (a small core) without need of resorting to the melting-by-sulfur differentiation concept.

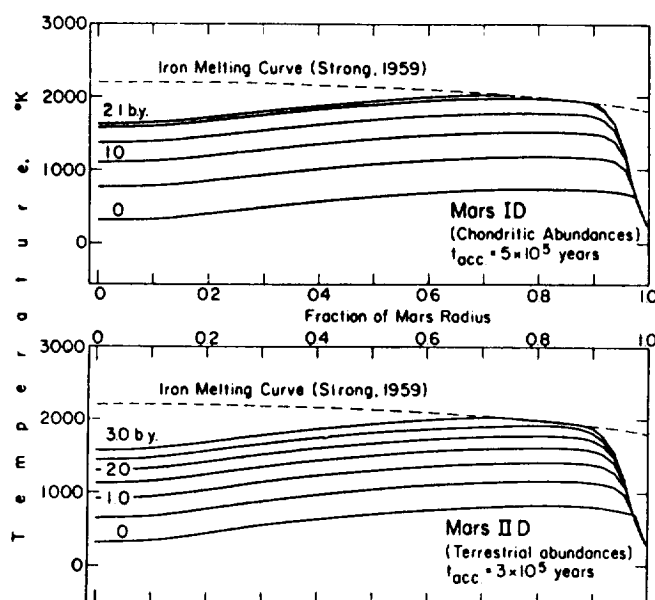


Fig. 5. Temperature profiles as a function of time (in billion years) for thermal history models Mars ID ("chondritic" radioactive abundances and $t_{acc} = 5 \times 10^5$ years) and Mars IID ("terrestrial" radioactive abundances and $t_{acc} = 3 \times 10^5$ years). (Hanks and Anderson, 1969)

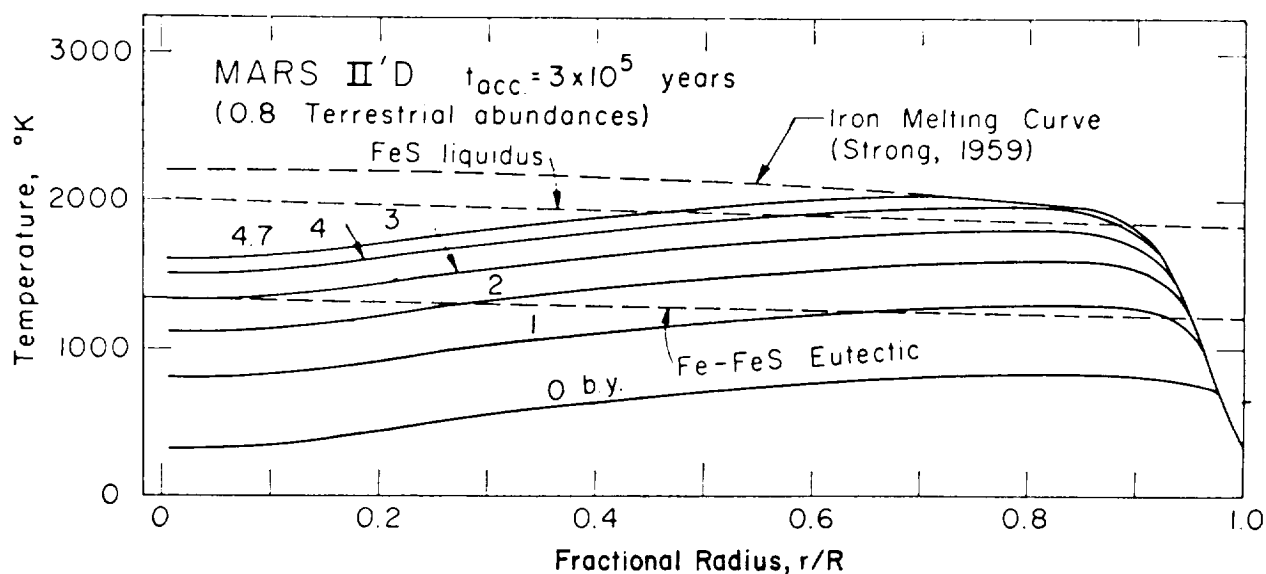


Fig. 6. Temperature profiles as a function of time (in billion years) for thermal history model Mars II'D (reduction to 0.8 of the "terrestrial" radioactive abundances and same $t_{acc} = 3 \times 10^5$ years as in Mars IID). (Hanks and Anderson, 1969)

Note: Dashed lines for FeS liquidus and Fe-FeS eutectic were added later by Anderson (1972), in consideration of his new differentiated internal density models. No revised profiles have yet been calculated to take into account differentiation possibilities.

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3.1 THERMAL PROPERTIES

INTRODUCTION

This section discusses Mars' surface and subsurface temperatures, their spatial and temporal variations, and the thermal properties derivable therefrom.* Observed temperatures have been obtained by remote sensing (radiometry) and are treated under two separate headings: (1) Infrared Radiometry, which provides surface temperatures exclusively; and (2) Microwave Radiometry, which provides subsurface temperatures. The theoretical temperatures expected are derivable for Mars from physical theory and available astronomical and physical data. These theoretical temperatures are treated first as background data for understanding the observed temperatures and their implications in terms of the thermal properties of the Martian surface.

The surface thermal environment of Mars differs from that of Earth in two ways: (1) the mean surface temperature of Mars is much lower because of the greater solar distance; and (2) diurnal thermal amplitudes are much larger because of the thin, dry atmosphere and lack of heat-storing oceans. Mars resembles Earth in its diurnal and annual thermal rhythms, but Martian seasonal periods are nearly twice as long and display much more north-south asymmetry.

3.1.1 THEORETICAL TEMPERATURES

The orbital and mechanical data for the planet Mars are well known (see Section 1) and the atmosphere is thin enough to be neglected in a first approximation, so that it is a relatively easy matter to calculate representative simplified thermal models (of surface and subsurface temperature variation and distribution), in the same general manner as for the Moon (insolation and heat conduction of an airless, smooth, homogeneous body). The temperatures closely follow the insolation in its diurnal and annual rhythms, at any given location, while the differences between contiguous areas depend upon their albedo, local slopes, and thermophysical parameters such as infrared emissivity and thermal inertia. Such models are meaningful only if the values of these parameters are correctly chosen, a choice which is itself guided by a comparison of observations with previous modeling results.

If the atmosphere is included, by taking into account some of its effects on surface temperature, such as infrared back-radiation (greenhouse effect), condensation/sublimation of volatiles (CO_2 and H_2O), turbulent convection in the lowest atmospheric layers, etc., then more meaningful models can be derived, but the calculations become more complicated.

Thus, thermal models with increasing degrees of sophistication can be constructed for Mars surface environment. Only the highlights of two such

*Temperatures above the surface (atmospheric temperatures) are not treated here; they are discussed in Sections 5.3 and 5.4 which cover the Lower and Upper Atmosphere, respectively.

models involving the atmosphere are given here; those of Leighton and Murray (1966) and of Kieffer (Neugebauer, et al., 1971).

It is necessary, however, to caution the reader that while such thermal models (which supply both spatial and temporal temperature distributions for the Martian globe over one Martian year) are most useful in that they supplement the meager observational information obtained so far, their theory and calculations still rely upon a number of simplifying assumptions. Also, the choice of values for the thermophysical or other parameters may not be adequate. Therefore, the models represent at best only rough approximations of the true distributions. The assumptions made and values of parameters chosen will be indicated where applicable.

Thermal Models - General

All thermal models of the Martian surface have as their basis the plane-parallel, homogeneous, one-dimensional, partial differential equation for sub-surface heat conduction: $\partial T / \partial x = K / \rho c \cdot \partial^2 T / \partial x^2$, where T is the absolute temperature, x is the vertical depth measured downward from the surface, K is the thermal conductivity, ρ the density, and c the specific heat. The boundary conditions are that (1) the net thermal energy flux at the surface ($x = 0$) must be equal at all times to the difference between the absorbed energy and the radiated energy, and (2) the temperature is constant at some depth $x = \ell$. The absorbed energy, neglecting atmospheric effects, is due to solar insolation and is proportional to $(1-A)$, where A is the Bolometric Bond Albedo (see Section 3.2). The radiated energy is $\epsilon \sigma T^4$, where ϵ is the surface emissivity, σ is the Stefan-Boltzmann constant, and T is the surface absolute temperature.

The solutions obtained from the diurnal surface temperature variation are found to depend on the "thermal inertia," $I = (K\rho c)^{1/2}$. A very low thermal inertia of $0.001 \text{ cal cm}^{-2} \text{ sec}^{-1/2} \text{ deg K}^{-1}$, as may be found on the Moon, is indicative of dust or powdered rock in a vacuum. Terrestrial rocks have thermal inertias near 0.05. As thermal inertia increases, the diurnal temperature amplitude decreases, and maximum temperatures occur later in the afternoon. A more detailed discussion is given by Sinton and Strong (1960a).

Atmospheric Effects

The Martian atmosphere slightly modifies the surface heat balance and surface temperature expected for an idealized planet without an atmosphere. Several effects are recognized:

- 1) Effective Thermal Conductivity. The comparatively extensive literature on the thermal properties of rock powders in a vacuum is largely inapplicable to Mars, as the conductivity of the Martian atmosphere alone, approximately 2.2×10^{-5} (pure CO_2 at 200°K), exceeds the conductivity of the lunar surface. In a vacuum, radiative heat transfer can contribute to the effective conductivity. The size of the contribution is proportional to T^3 (Watson, 1964). Fountain and West (1970) have shown that under simulated Martian conditions this radiative effect is small in comparison with pure conduction. Therefore, temperature-independent conductivity is appropriate for the Martian conditions.

- 2) Infrared Back-Radiation (CO₂ greenhouse effect). While a predominantly CO₂ atmosphere is practically transparent to incoming solar radiation, the outgoing thermal radiation undergoes selective absorption. For blackbody radiation in the 200-300°K range, the 15 μ band of CO₂ is the prime contributor to this Martian atmospheric thermal opacity. Some of this energy is reradiated back to the surface, producing a weak greenhouse effect.
- 3) Turbulent Heat Conduction. Turbulent heat transfer across the boundary layer has been considered by Gierasch and Goody (1968). The primary effect is to decrease the surface-temperature diurnal variation by a few degrees, corresponding to an apparent increase of thermal inertia.
- 4) Condensation/Sublimation of CO₂. The condensation temperature of CO₂ is dependent on its pressure, but at Martian surface pressures (see Section 5.2) it falls in the range of 145-150°K. When surface temperatures on Mars reach these values, CO₂ condenses, releasing its latent heat and inhibiting any further temperature drop. Similarly, deposits of CO₂ ice inhibit temperature rises until sublimation is complete. The rate of mass formation (and the subsequent sublimation) of CO₂ ice per-unit-area at the surface of Mars has been calculated by Leighton and Murray (1966).
- 5) Screening and Blanketing by Clouds or Aerosol (Dust) Layers. While these effects have not been studied in detail for the Mars environment, they should generally decrease the surface temperature in daytime (by absorption of solar radiation) and increase it at night (by back-radiation). The effects are usually local in extent and certainly highly variable. Gierasch (1971) has made preliminary calculations on the formation of CO₂ clouds in the Martian atmosphere and their radiative effects. Aleshin and Fedoseeva (1970) calculated that a dust-laden CO₂ atmosphere model at 5-mb pressure would cause the predawn temperatures to increase by as much as 30°K.

Leighton-Murray Thermal Model

Leighton and Murray (1966) were the first to construct a thermal model of the Martian surface including the effects of CO₂ condensation and sublimation. They incorrectly assumed that the CO₂ greenhouse effect could be accounted for by reducing the apparent infrared surface emissivity by 10 percent. An error was also made in the placement of the aphelion, relative to northern summer solstice. In spite of these errors, the model provides a fair idea of the gross thermal conditions at the surface of Mars and in its subsurface. Figure 1 depicts their results in terms of diurnal surface temperature curves for the equator near the autumnal equinox of Mars. The variation of the average temperature of the disk, as viewed from the Sun, is shown as a function of season and depth in Fig. 2. The results of calculations of mean annual temperatures as a function of latitude are shown in Fig. 3. Condensation temperatures of water vapor are also indicated in Fig. 3.

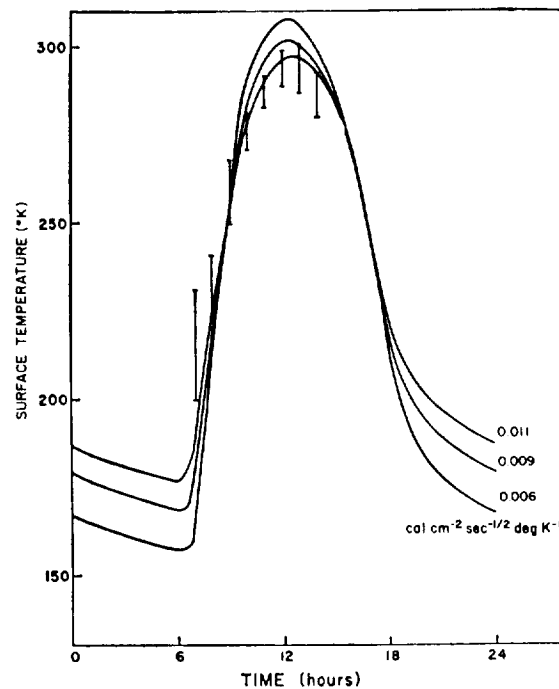


Fig. 1. Theoretical curves of diurnal variation of surface temperature near the equator at southern spring equinox (approximate seasonal date). Sinton and Strong (1960a) observations are compared. (Leighton and Murray, 1966)

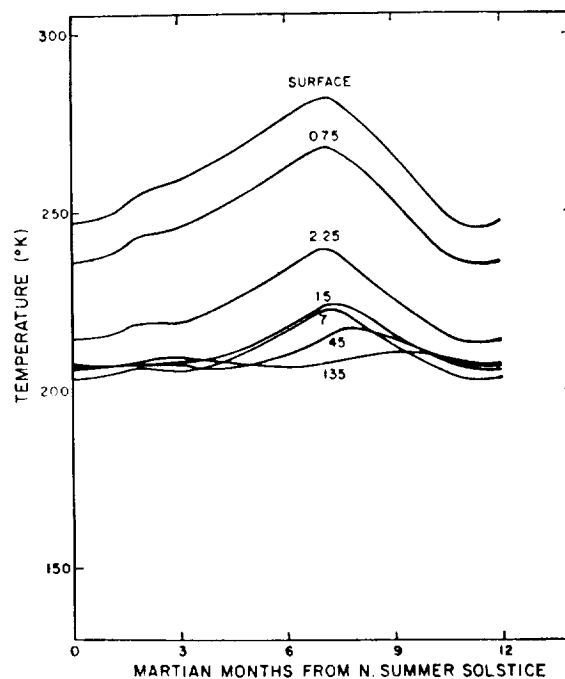


Fig. 2. Theoretical curve of annual variation of average temperature of the disk as viewed from the Sun for various depths in centimeters (using the CO_2 condensation model). (Leighton and Murray, 1966)

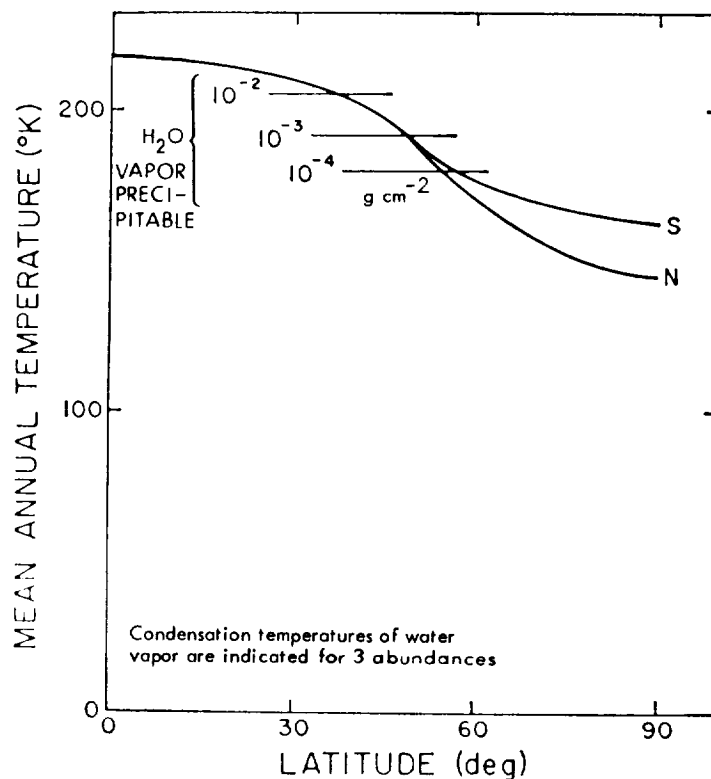


Fig. 3. Average annual surface temperature as a function of latitude (using the CO₂ condensation model). (Leighton and Murray, 1966)

The best fit with the Sinton and Strong (1960) radiometric data was obtained with the following parametric values:

$$\text{Thermal Inertia, } (K\rho c)^{1/2} = 0.009 \text{ cal cm}^{-2} \text{ sec}^{-1/2} \text{ deg K}^{-1}$$

$$\begin{aligned} \text{Bolometric Bond Albedo, } A &= 0.15 \text{ for Martian dark areas} \\ &= 0.65 \text{ for polar ice caps} \end{aligned}$$

$$\text{Surface Emissivity (8-12 } \mu\text{), } \epsilon_{10} = 0.85 \text{ for bare ground and polar ice caps}$$

Kieffer Thermal Model

H. Kieffer has constructed thermal models similar in nature to the Leighton-Murray model for the purpose of interpreting Mariner 1969 IR Radiometry data (see Neugebauer, et al., 1971). These homogeneous ground conduction models assume (as in the L-M model) temperature-independent conductivity and specific heat. The orbital geometry error of the L-M model was corrected, and the greenhouse effect was accounted for by using a constant atmospheric back-radiation equal to 0.01 of the local noon solar flux. Turbulent heat transfer across the boundary layer was not included in the models, but was estimated to correspond to a 10 percent increase in the apparent thermal inertia. CO₂ condensation and sublimation was included in the models.

Figures 4 and 5 show the resulting diurnal surface temperature variation at perihelion (Fig. 4), and at aphelion (Fig. 5). Perihelion ($r = 1.381$ AU, $\eta = 335^\circ$) corresponds closely to northern winter solstice, while aphelion ($r = 1.666$ AU, $\eta = 155^\circ$) corresponds to northern summer solstice. Curves are depicted for latitudes 0° , $\pm 30^\circ$, $\pm 45^\circ$, and $\pm 60^\circ$. Curves for the equinoxes do not differ much from being intermediate between the extreme positions.

The parametric values adopted were:

$$\text{Thermal Inertia, (Kpc)}^{1/2} = 0.004 \text{ to } 0.010 \text{ cal cm}^{-2} \text{ sec}^{-1/2} \text{ deg K}^{-1}$$

$$\text{Bolometric Bond Albedo, } A = 0.20 \text{ to } 0.40$$

$$\text{Surface Emissivity (8-12 } \mu\text{), } \epsilon_{10} = 0.90$$

3.1.2 INFRARED RADIOMETRY

The relationship between incident solar radiation, reflected solar radiation, and emitted thermal radiation from Mars is discussed in Section 3.2.2. It can be summarized by stating that the amount of incident solar energy absorbed by the surface of Mars, must be balanced by an equal amount of thermal energy radiated from Mars. It is this emitted thermal energy that can be measured using infrared and microwave radiometry. For temperatures between 150° and 300° K, most of the energy is emitted in the 5 to 30 μ wavelength range. Infrared radiometric measurements of the Martian surface are made at these wavelengths. If Mars were an ideal blackbody radiator, the radiometrically observed energies could be directly interpreted as surface temperatures by means of Planck's blackbody radiation equation. However, Mars surface does not radiate precisely like a blackbody, because of selective absorption of the thermal radiation by the Martian surface and atmosphere. This results in a slight redistribution of the energy. At a given wavelength, the observed brightness temperature can be converted to an actual surface temperature, only if the effective emissivity is known or assumed.

The atmosphere of Mars is generally transparent to visible and infrared light, except for absorption at selected wavelengths due to carbon dioxide and small amounts of water and other trace constituents (see Section 5). Martian polar regions are obscured in wintertime by the polar hoods, and other regions of the planet are occasionally obscured by dust or clouds. Observations of the Martian surface from Earth are hindered primarily by absorption in the Earth's own atmosphere (see Fig. 6). Earth-based infrared radiometric observations can be made only through the atmospheric windows, such as the 8-14 micron window. Other disadvantages in observing Mars from Earth are those encountered at all wavelengths: (1) the planet is always at great distance, with the result that very small thermal fluxes are received and only low areal resolution is obtainable over the disk; (2) the relative orbital geometry of Mars and Earth restricts the phase angle range observable to $\pm 47^\circ$, thereby disclosing little of the nightside; (3) the inclination of the Mars equatorial plane with respect to the ecliptic can be great enough to conceal a large sector of latitudes centered on the more distant pole (at the time of the observation).

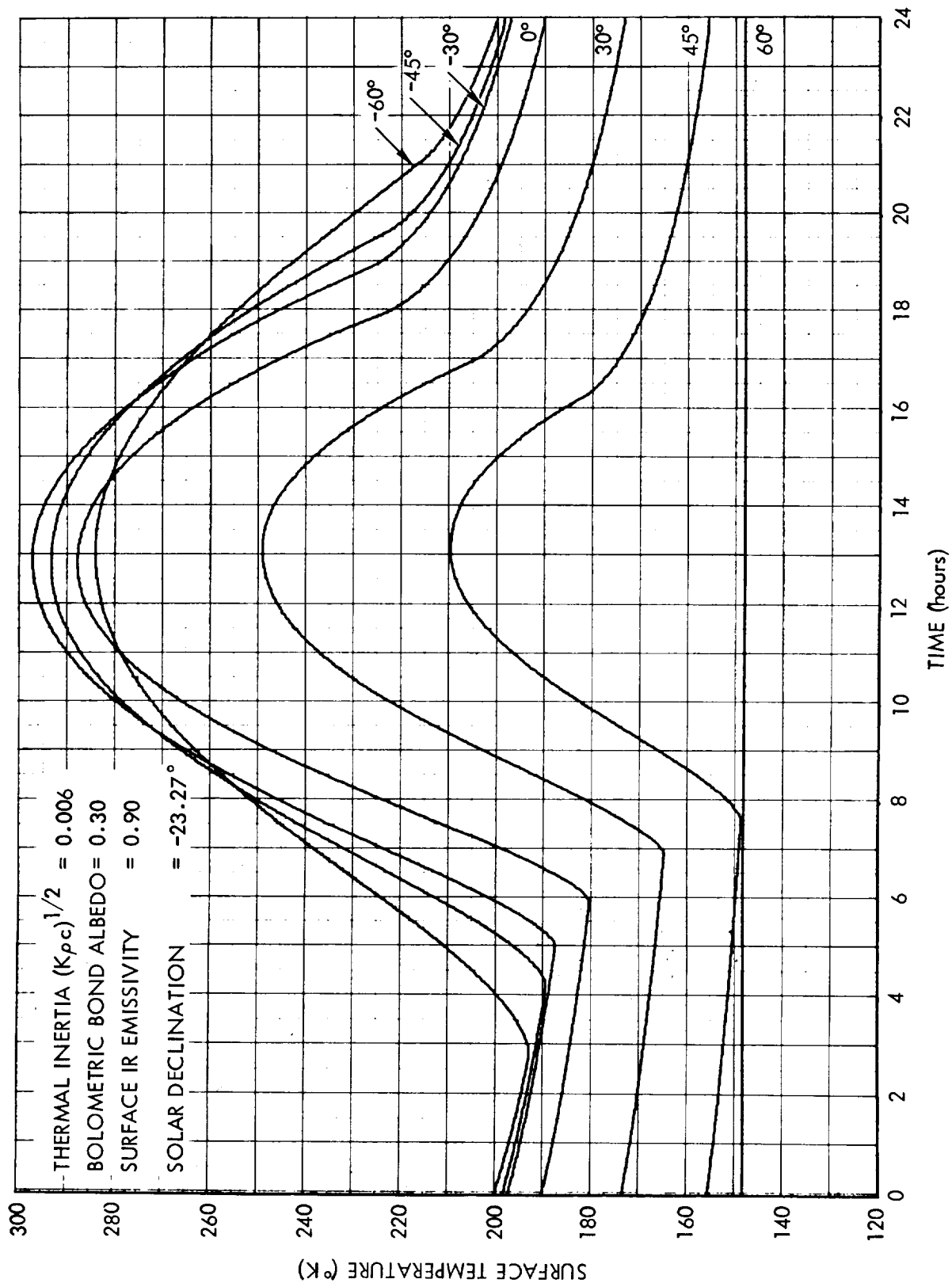


Fig. 4. Diurnal variation curves of surface temperature at perihelion for latitudes 0° , $\pm 30^\circ$, $\pm 45^\circ$, and $\pm 60^\circ$ (Kieffer, 1972).

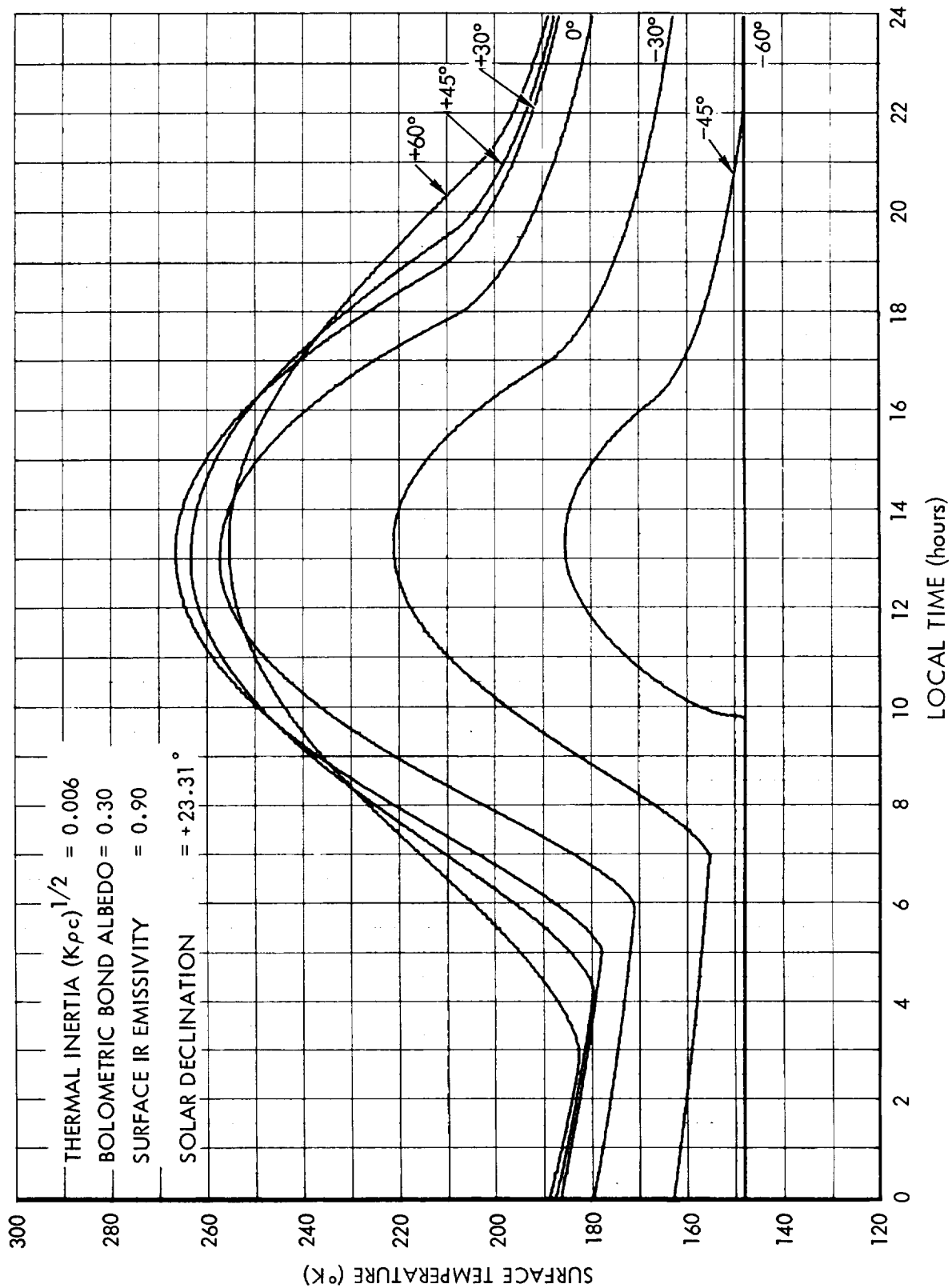


Fig. 5. Diurnal variation curves of surface temperature at aphelion for latitudes 0° , $\pm 30^\circ$, $\pm 45^\circ$, and $\pm 60^\circ$ (Kieffer, 1972).

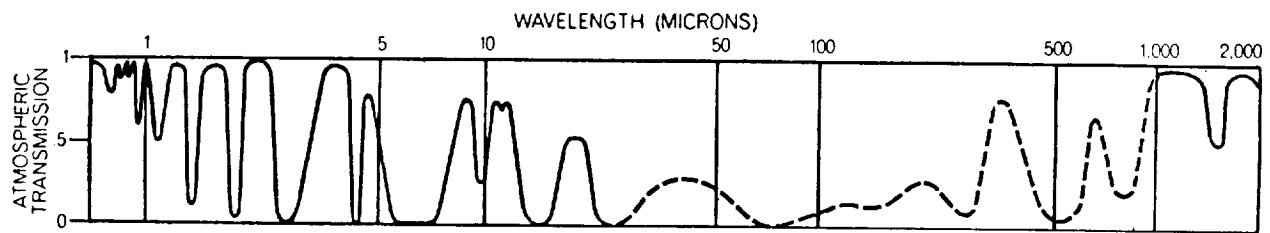


Fig. 6. Earth: atmospheric transmission (Murray and Westphal, 1965).

In the particular case of Mars, the concealed polar sector may extend down to the 74° latitude circle (i.e., 26° from the pole itself). Spacecraft astronomy meets with fewer hindrances; complete global coverage is possible over dayside or nightside (subject only to instrument pointing constraints and time available for observations), and the areal resolution and accuracy attainable are far superior.

To date, only two sets of modern reliable, infrared radiometric information on Mars exist.* Together, these measurements cover only six days of the southern spring season. The main difference between them lies in their areal resolution and surface coverage, as follows:

- 1) Low-resolution (500 km) but extensive (within $\pm 70^\circ$ latitude) measurements from Earth's largest telescope (200-inch aperture) during four days (end of July 1954) by Sinton and Strong (1960a, b). Only dayside measurements from 7 a.m. to 3 p.m. Martian local time.
- 2) High-resolution (50 km) but limited (2 percent of Mars surface) measurements from Mariner 6 and 7 spacecraft during two days (July 31 and August 5, 1969). Tracks crossed the equatorial and southern Martian regions, and included the South Polar Cap and early nightside sampling.

*Earlier radiometric information, obtained at Lowell Observatory by Coblentz and Lampland between 1922 and 1942 (see Coblentz and Lampland, 1927), and reduced by Gifford (1956), is extensive, covering three Martian seasons. However, the temperature measurements are of limited accuracy. These measurements are not considered here, nor are those of Pettit and Nicholson (1924) at Mt. Wilson Observatory, belonging rather to the category of 'historical observations'. Their value lies more in the preliminary observational insight on Martian climatology which they provided at the time.

Infrared Radiometry From Earth

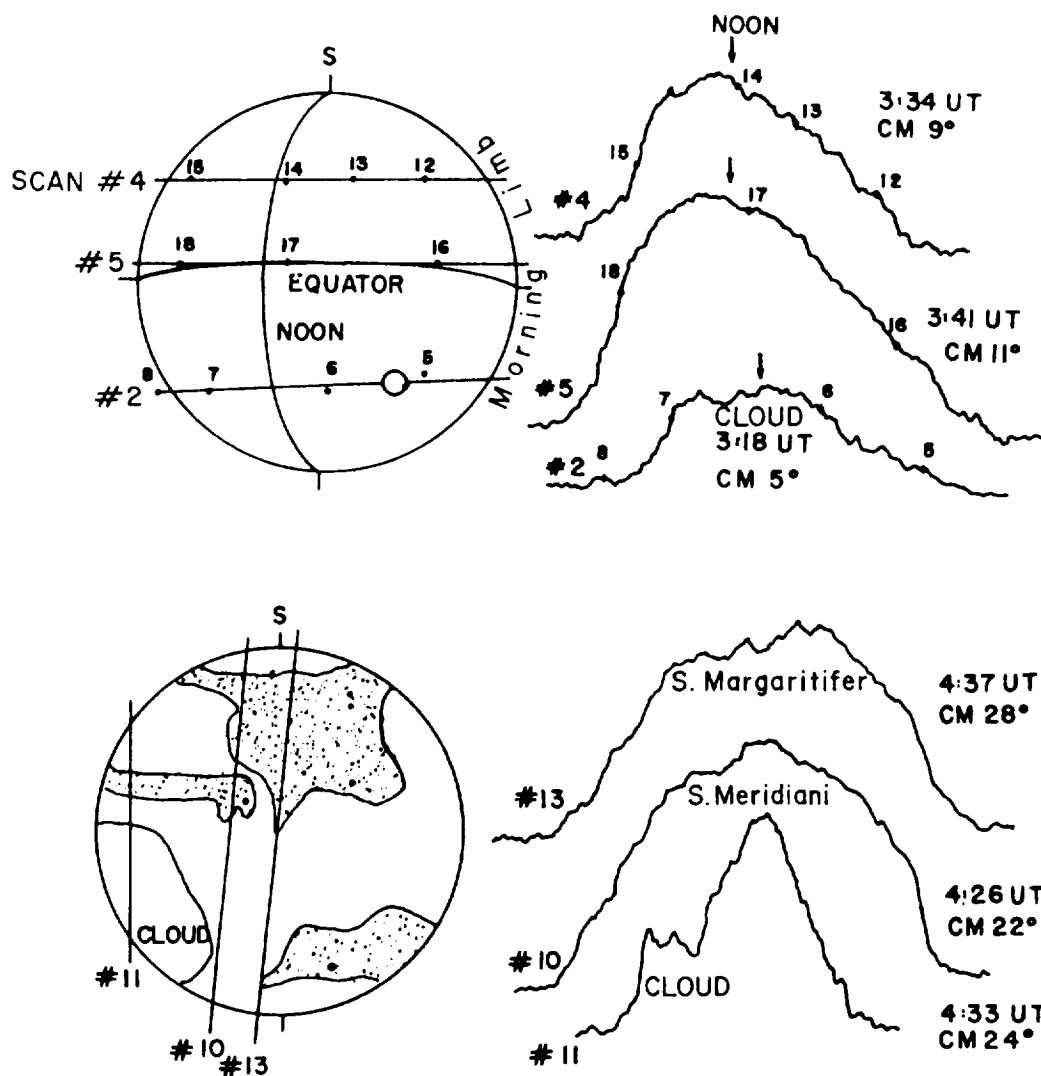
The history of ground-based infrared radiometry of planets is given by Sinton and Strong (1960b), along with their data for Venus and Mars (July 1954) and description of their observing equipment. Examples of their scan data are given in Fig. 7. Of the 33 scans obtained, only 6 equatorial scans were reduced by Sinton and Strong (1960a). The entire set was analyzed by Morrison (1968). He reduced the same equatorial scans as Sinton and Strong and obtained kinetic temperatures as depicted in Fig. 8. The T_1 values (Fig. 8) are derived assuming an isotropic emissivity of 0.95, while T_2 values are obtained with a lunar variation of emissivity with direction (Sinton, 1962), normalized to a mean of 0.95. The model curves shown are for a homogeneous planet with no atmosphere. Morrison grouped all of the data into regions $10^\circ \times 10^\circ$ in latitude and local time, and constructed the brightness temperature contours shown in Fig. 9. The season on Mars was early southern spring (heliocentric longitude $\eta \sim 290^\circ$).

Morrison also grouped the data according to bright and dark areas. Adopting a bolometric albedo $A = 0.25$ for the bright areas, and an emissivity, ϵ , of 0.93, he concluded that the thermal inertia was $0.004 \text{ cal cm}^{-2} \text{ sec}^{-1/2} \text{ deg K}^{-1}$. A similar calculation for the dark areas (using $A = 0.15$ and $\epsilon = 0.93$) led to a thermal inertia of 0.006. Using these values, Morrison proceeded to compute the expected temperature distribution with latitude and local time for the two types of areas when Mars is at the northern autumnal equinox ($\eta = 265^\circ$). The results are depicted in Fig. 10. He concluded that dark areas are always hotter than bright areas, although during midmorning this difference is very small. The greatest temperature differences, about 15° K , develop near sunset and persist throughout the night.

Grouping the north-south scan data for bright areas into three intervals of local time, Morrison plotted the average brightness temperature versus latitude for $\eta \sim 290^\circ$. These are shown in Fig. 11, where for comparison the curve of derived peak kinetic temperatures for bright areas has been added. The fit is fair for northern latitudes, but the data drops much more rapidly in the southern hemisphere than the theoretical curve. The difference is probably due to seasonal effects, including the presence of a large southern polar cap. These were not included in Morrison's model.

To summarize the values of the assumed or derived thermal parameters obtained by Morrison from Sinton and Strong's data:

Bolometric Albedo, A	= 0.25 for bright areas = 0.15 for dark areas
Surface Emissivity (8-13 μ), ϵ_{10}	= 0.93
Thermal Inertia, $(K\rho c)^{1/2}$	= $0.004 \text{ cal cm}^{-2} \text{ sec}^{-1/2} \text{ deg K}^{-1}$ for bright areas = 0.006 for dark areas
Specific Heat Capacity, c	= $\text{cal g}^{-1} \text{ deg K}^{-1}$



NOTE: Scan #2, which crossed a large yellow cloud, is relatively flat and cold. Circle represents scanning aperture (1.5 arc sec). Abbreviation C.M. means central meridian and UT universal time.

Fig. 7. Radiometric drift-curves across Mars on July 20, 1954 ($\eta = 287.5^\circ$). Numbers on the scans match with those on chart and give positions at which photographs were taken. (Sinton and Strong, 1960a).

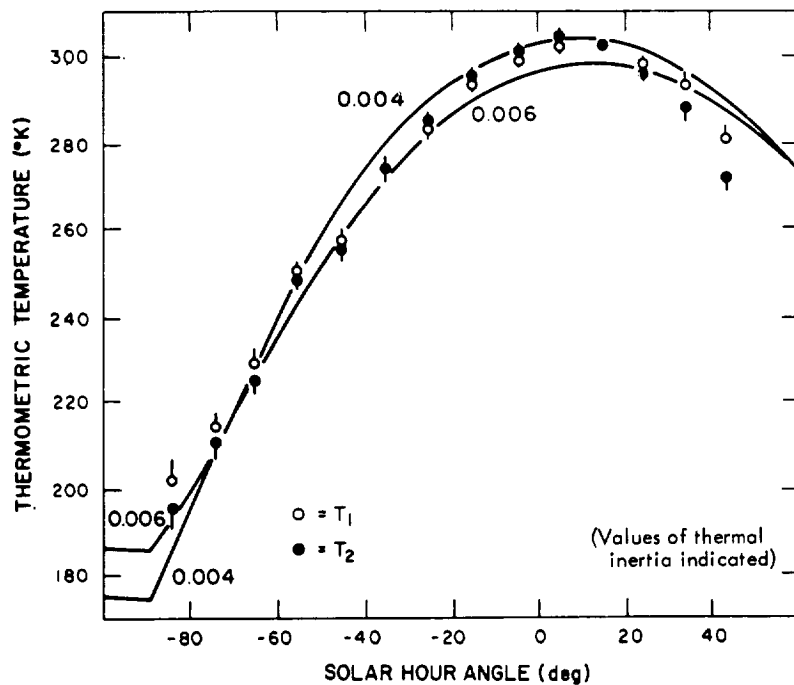


Fig. 8. Equatorial diurnal temperature variation on Mars in early southern spring ($\eta \sim 290^\circ$). (Morrison, 1968)

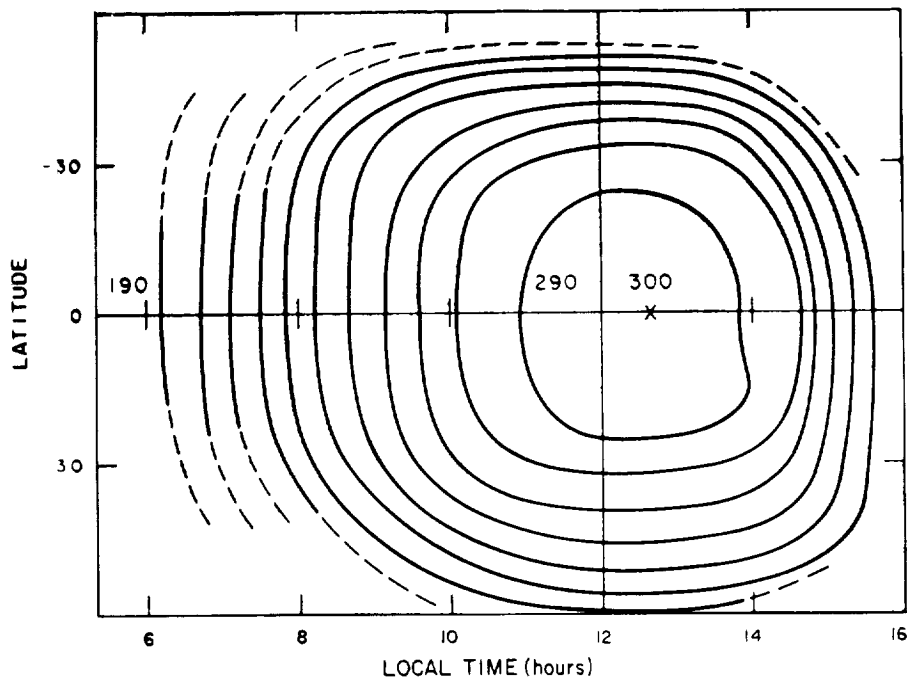


Fig. 9. Brightness temperature map of Mars in early southern spring ($\eta \sim 290^\circ$). All data from bright areas are included. (The dashed isotherms are known with less accuracy than the solid lines. Contour interval is 10°K .) (Morrison, 1968)

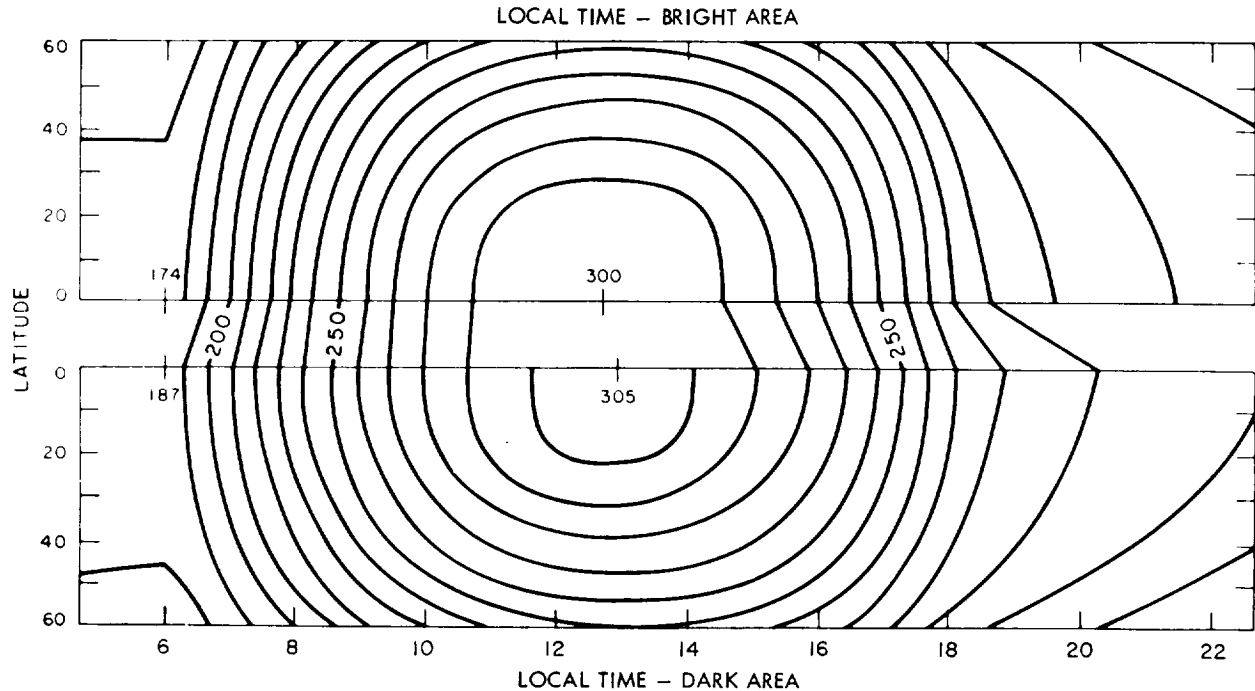


Fig. 10. Theoretical temperature distribution with latitude and local time for Mars at the northern autumn or southern spring equinox ($\eta = 265^\circ$).

The upper map was computed for bright areas: albedo, 0.25 and thermal inertia, $0.004 \text{ cal cm}^{-2} \text{ sec}^{-1/2} \text{ deg}^{-1}$. The lower map represents dark areas: albedo, 0.15 and thermal inertia, $0.006 \text{ cal cm}^{-2} \text{ sec}^{-1/2} \text{ deg}^{-1}$.

(Morrison, 1968)

Density, ρ	$= 2 \text{ g cm}^{-3}$
Thermal Conductivity, K	$= 5 \times 10^{-5} \text{ cal cm}^{-1} \text{ sec}^{-1} \text{ deg K}^{-1}$ for bright areas
	$= 12 \times 10^{-5}$ for dark areas

Infrared Radiometry From Spacecraft

Mariners 6 and 7 each carried a two-channel infrared radiometer designed to measure the thermal emission of Mars surface (and thereby the equivalent blackbody temperature) at an areal resolution of about 50 km. The two spectral channels (8.1 to 12.5μ and 17.9 to 25.1μ) were chosen to avoid interference from atmospheric CO_2 emission and to correspond approximately to the peaks of the blackbody curves for 300°K and 150°K , respectively. A description of the instrument has been given by Chase (1969).

The final results of the IRR experiment have only recently been published (Neugebauer et al., 1971). Measurements made during the approach phase of the flyby did not exceed Earth-based data in resolution and suffer from insufficient data regarding the precise pointing angle of the instrument. The measurements were used primarily as a check on the prelaunch instrument

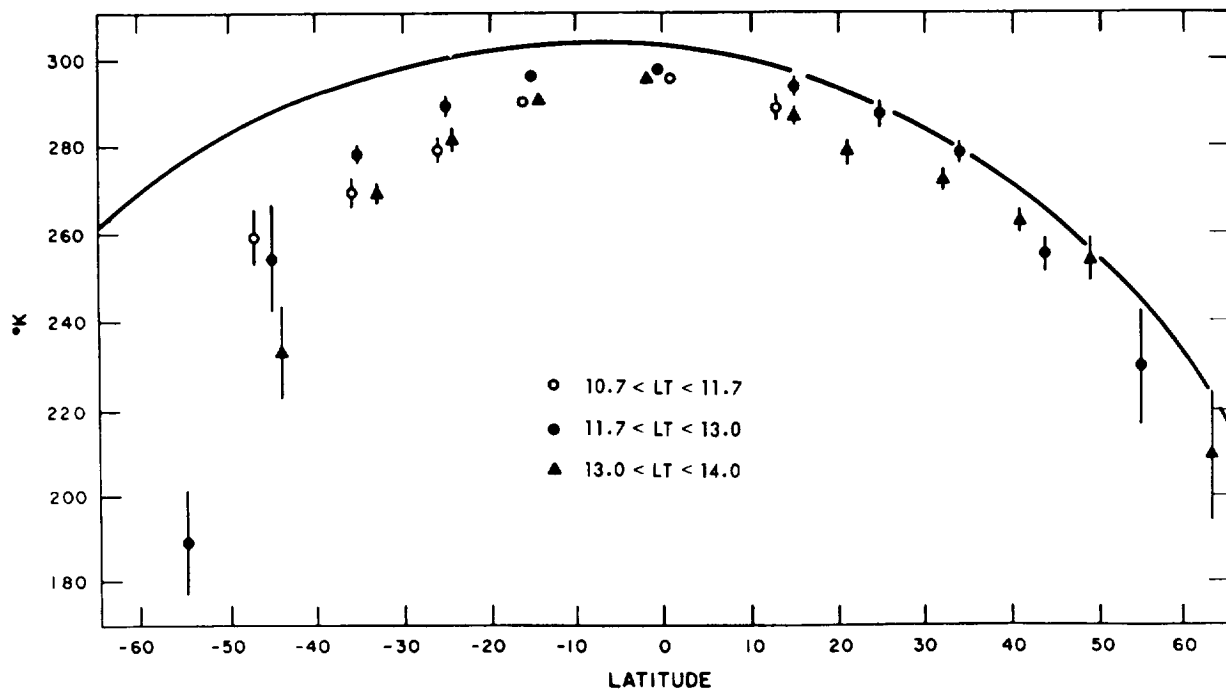


Fig. 11. Variation of temperature with latitude on Mars in early southern spring ($\eta \sim 290^\circ$). The data points are average brightness temperatures with indicated standard deviations in the mean. The solid curve is the theoretical peak thermometric temperature for an albedo of 0.25 and a thermal inertia of $0.004 \text{ cal cm}^{-2} \text{ sec}^{-1/2} \text{ deg}^{-1}$. This curve should be above the data points by less than 10°K . (Morrison, 1968)

radiometric calibration. Results of the near-encounter phase are given in terms of plots of kinetic temperatures versus local Mars time, as shown in Figs. 12 and 13. The actual scan traces, across Mars, are shown in Figs. 14, 15, and 16, where the 10μ kinetic temperatures and the difference between 10 and 20μ temperatures have also been plotted as reference data. The Meridiani Sinus region was the only area viewed (during near-encounter phases) by both spacecraft. Mariner 6 primarily scanned the equatorial region of Mars while Mariner 7 scanned from Meridiani Sinus to the South Polar Cap and then northward through Hellas. Only about two percent of Mars was covered by these scans. The derived temperatures were estimated to have a relative accuracy of 0.5°K and an absolute accuracy of 2°K , except at the South Polar Cap, where depressed temperatures and field-of-view corrections reduced the absolute accuracy to about 5°K .

In order to reduce brightness temperatures to kinetic temperatures, a value for the surface emissivity had to be assumed. Based on the best $8\text{-}12 \mu$ laboratory measurements of the emissivity of terrestrial materials (Hovis and Callahan, 1966) a mean Martian emissivity of $\epsilon_{10} = 0.90$ was adopted. By minimizing the differences $\Delta T = T_{20} - T_{10}$ over all the data, a long wavelength channel emissivity $\epsilon_{20} = 0.88 \pm 0.03$ was derived, along with $\alpha = 0.10 \pm 0.07$ for the exponent α characterizing the $\cos^\alpha \theta$ angular dependence law. The only

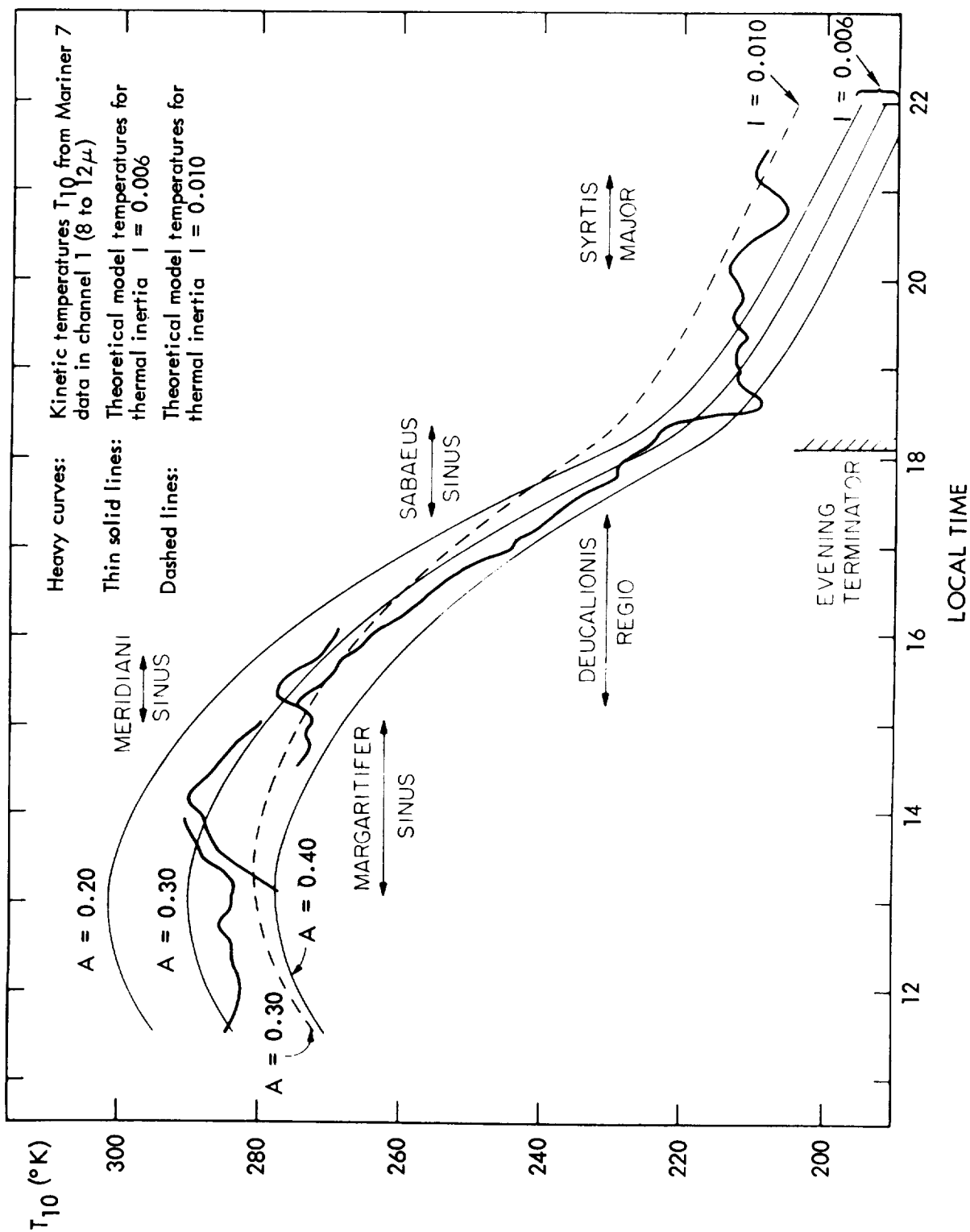


Fig. 12. Surface kinetic temperatures versus local time, obtained by the Mariner 6 IRR swaths. Comparison theoretical temperature curves (using different bolometric bond albedos and thermal inertias) are also shown. (Neugebauer et al., 1971)

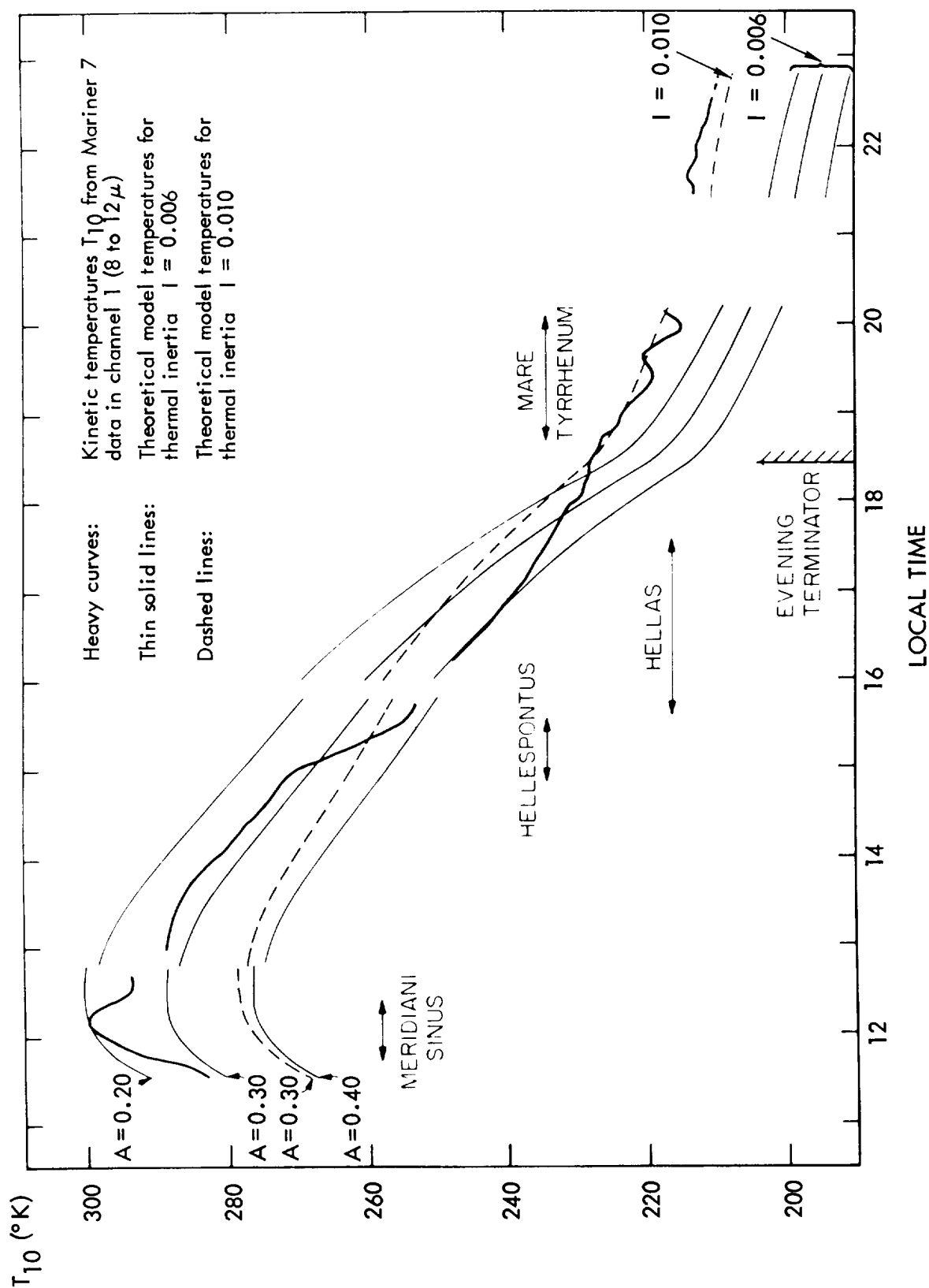


Fig. 13. Surface kinetic temperatures versus local time, obtained by the Mariner 7 IRR swaths. Comparison theoretical temperature curves (using different bolometric bond albedos and thermal inertias) are also shown. (Neugebauer et al., 1971)

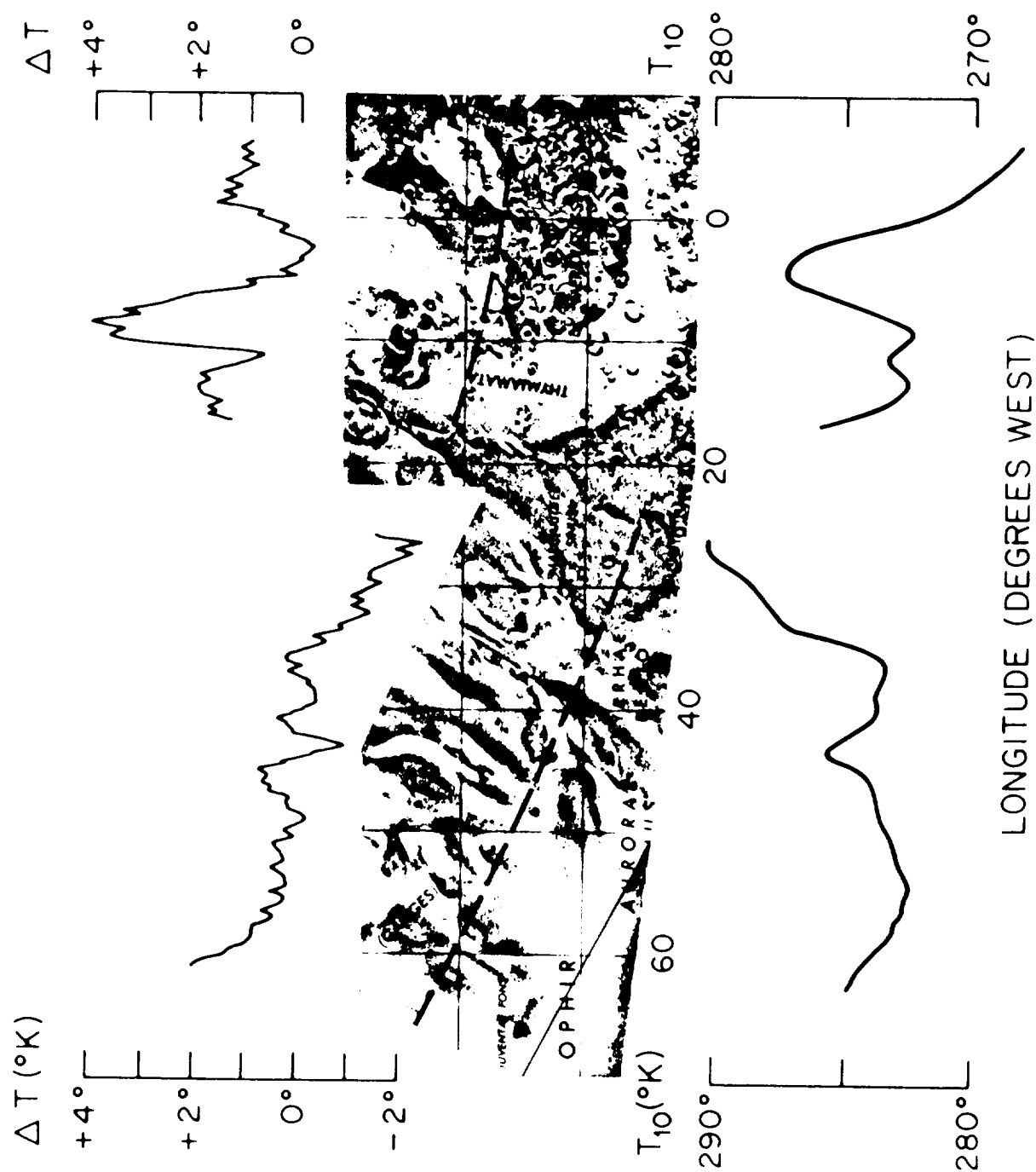


Fig. 14. Surface kinetic temperatures along 2 swaths of Mariner 6 between latitudes 5°N and 20°S.
(Neugebauer et al., 1971)

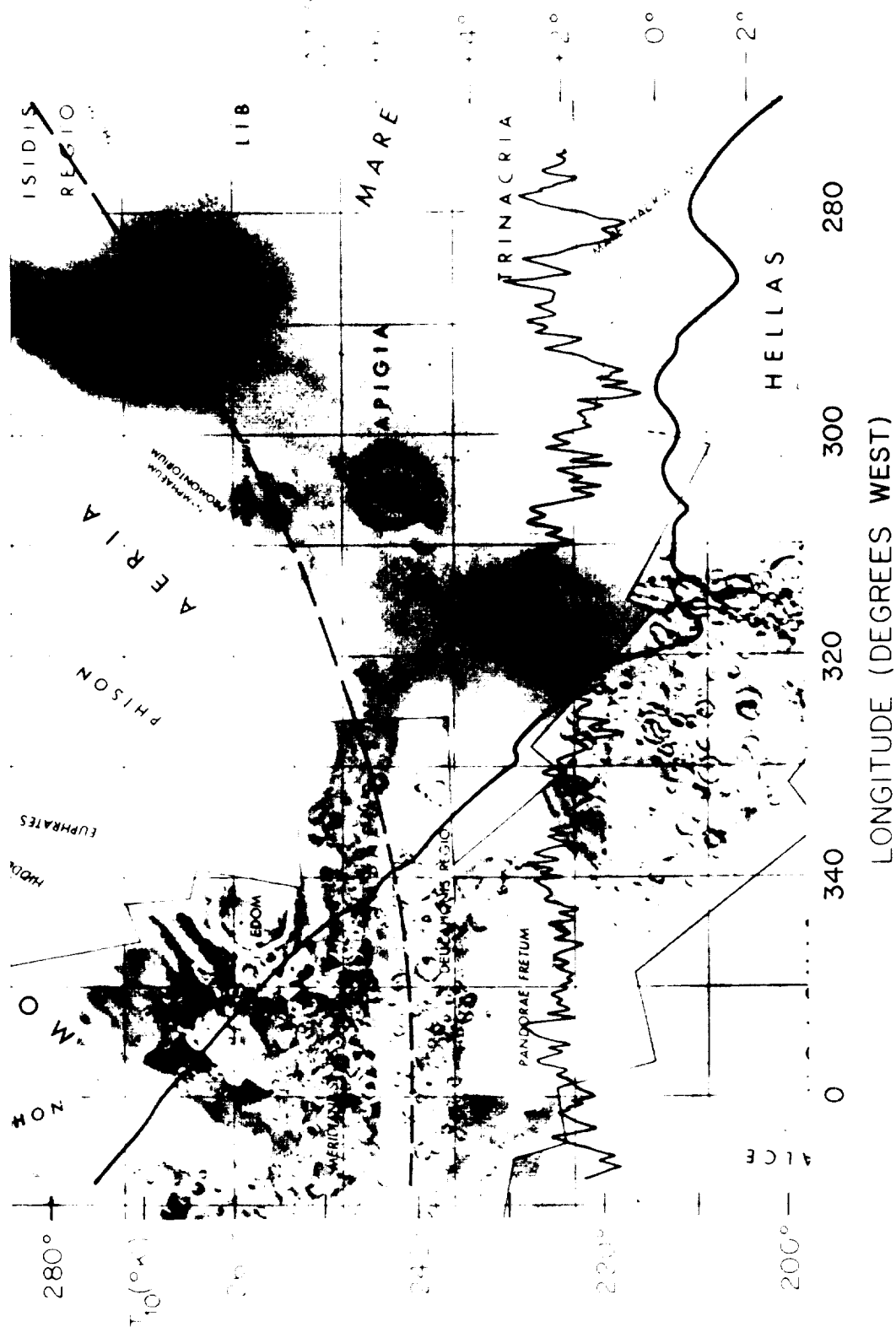


Fig. 15. Surface kinetic temperatures along 1 swath of Mariner 6 between latitudes 20°N to 15°S. (Neugebauer et al., 1971)

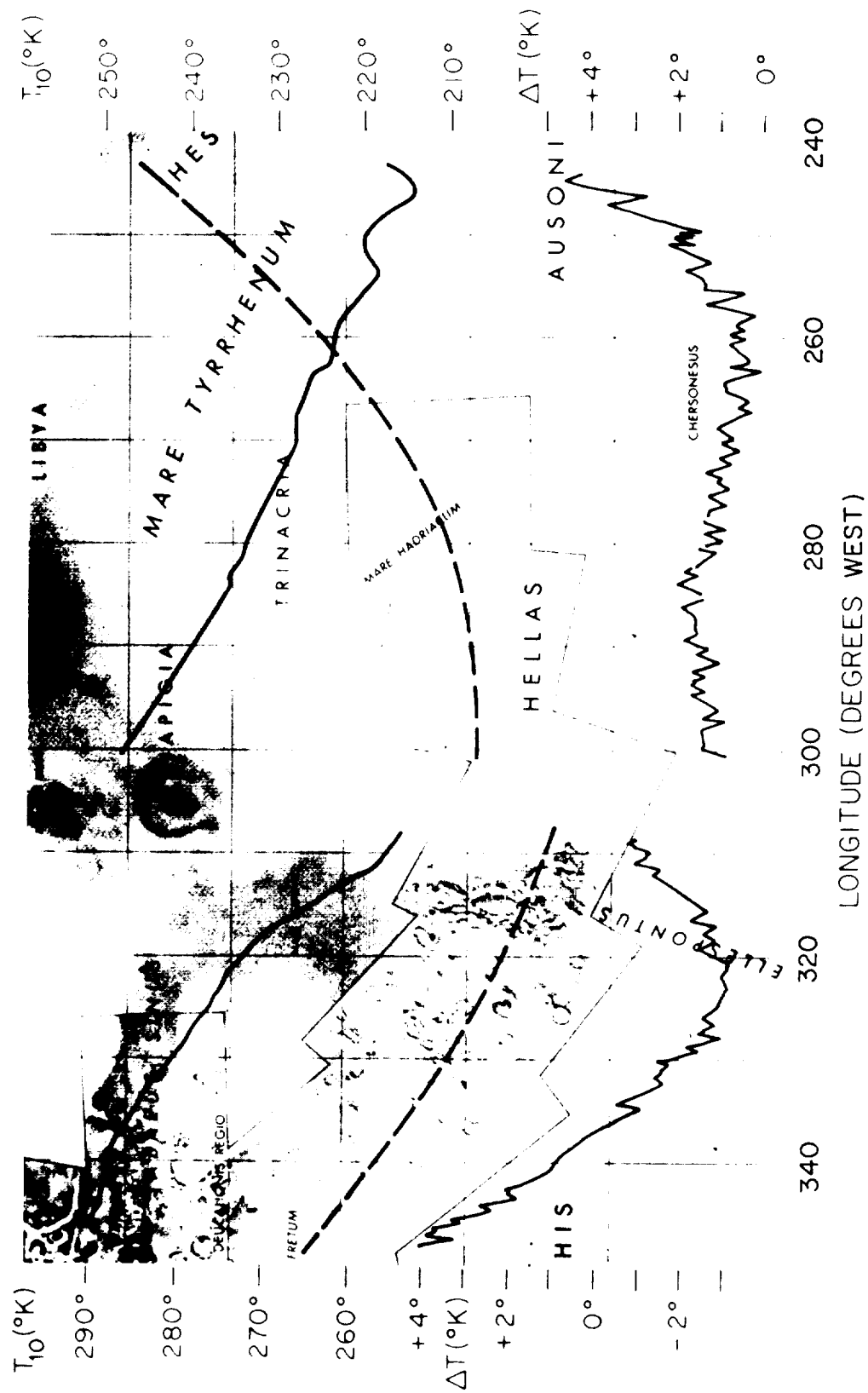


Fig. 16. Surface kinetic temperatures along 2 swaths of Mariner 7 between latitudes 10°S and 45°S . (Neugebauer et al., 1971)

instance where α could be directly determined from the observations was for a single area near Margaritifer Sinus, which was viewed at angles of 30° and 56° from the vertical. The value obtained was $\alpha = 0.17 \pm 0.05$, which is in fair agreement with the previously derived value.

Comparison of the observational data with Kieffer's model (Section 3.1.1) yielded a mean surface thermal inertia of $0.006 \text{ cal cm}^{-2} \text{ sec}^{-1/2} \text{ deg K}^{-1}$, with bolometric Bond albedo $A = 0.2$ to 0.4 . These values, which apply to the daytime measurements lead to temperatures for the nightside which are several degrees lower than observations. The discrepancy may be due to actual horizontal variations of the thermal inertia or alternatively, to vertical inhomogeneity.

A further complexity is added to the data analysis by the local topography of Mars. Although Mars surface temperature is unlikely to be strongly dependent on altitude (the tenuous Martian atmosphere is probably thermally decoupled from the surface in a first approximation), any slope which deviates from that of a perfect sphere causes the solar insolation, at that point, to differ from the insolation assumed for the models. In the late afternoon or early evening, such slopes could cause temperature differences of more than $\pm 1^\circ \text{K}$ for each degree of slope. These differences cannot be modeled until a detailed topographic map of Mars is available.

The IRR investigators concluded that the surface of Mars appears to be strongly nonhomogeneous in its thermal properties, on scales ranging from those of the classical light and dark areas to the limit of resolution of the radiometers. The derived or assumed thermal parameters are summarized below:

Bolometric Albedo, A	$= 0.2 \text{ to } 0.4$
Surface Emissivity, ϵ_{10}	$= 0.90 \cos^{0.10 \pm 0.07} \theta$
ϵ_{20}	$= 0.88 \cos^{0.10 \pm 0.07} \theta$
Thermal Inertia, $(K\rho c)^{1/2}$	$= 0.006 \text{ to } 0.010 \text{ cal cm}^{-2} \text{ sec}^{-1/2} \text{ deg K}^{-1}$
Specific Heat Capacity, c	$= 0.16 \text{ cal g}^{-1} \text{ deg K}^{-1}$
Density, ρ	$= 1.3 \text{ to } 2.0 \text{ g cm}^{-3}$
Thermal Conductivity, K	$= 1 \text{ to } 3 \times 10^{-4} \text{ cal cm}^{-1} \text{ sec}^{-1} \text{ deg K}^{-1}$

For the probable materials on Mars' surface, thermal conductivity depends primarily on particle size, only slightly on porosity, and is not dependent on composition. Using the Wechsler and Glaser (1965) conductivity-particle size relation for silicate powders under 6 mb pressure, one may derive (for the K values above) mean particle sizes (diameters) of about 200μ for $I = 0.006$ and 1 mm for $I = 0.010$.

The low thermal emission of the polar cap could be measured with reasonable signal-to-noise ratios only in the 18 to 25μ range. The continuous

frost cover started south at about -62° latitude, and the viewing geometry became extreme by the end of the polar swath. The temperatures (T_{20}) measured over the cap proper have a greater uncertainty than those measured elsewhere (on bare or unfrosted ground). This was attributed to two main causes: (1) effects of the extended field of view, and (2) thermal offsets of the internal calibration plate (arising probably when viewing "empty space"). The first effect was estimated at no more than 2°K error (including noise and gain errors, etc.), by making use of a model of the cap at 148°K , the uncorrected observed minimum temperature. The thermal offset effect was determined to cause a 5°K uncertainty at the most. It was concluded that the temperature of the South Polar Cap was $148^{+5}_{-2}^\circ\text{K}$.*

3.1.3 MICROWAVE RADIOMETRY

Planck's blackbody radiation equation shows that for temperatures of 150° to 300°K (the range of Martian surface temperatures) most of the energy emitted is in the 5 to $30\ \mu$ wavelength region. At the much longer radio wavelengths, where the Rayleigh-Jeans approximation to Planck's law is valid, the emitted thermal energy is proportional to T/λ^2 , where T is the absolute temperature of the source, and λ is the wavelength. Although the available energy-per-unit wavelength is several orders of magnitude smaller in the microwave region than in the infrared region of the spectrum, measurements of the microwave spectrum at reasonably high signal-to-noise ratios are possible using large antennas and more sensitive signal detectors. However, since high angular resolution is difficult to obtain in the microwave region only integrated-disk measurements of thermal emission from Mars have been made. (To date, none of the spacecraft sent to Mars have carried microwave radiometers.) The strength of any microwave signal received is directly proportional to the solid angle subtended at Earth by the disk of Mars. For this reason, precision measurements have been limited to periods of near-opposition. The diurnal variation of microwave temperatures can only be obtained by measuring the disk at different phases due to the low spatial resolution.

As in the case of infrared radiometry, only the brightness temperatures can be directly measured. The actual kinetic temperatures can be deduced only if the appropriate emissivity is known. However, if the diffuse radar reflectivity of Mars is known at the same microwave wavelength, Kirchhoff's Law states that the emissivity will be equal to the absorptivity (and absorptivity = $1 - \text{reflectivity}$).

Temperatures observed in the infrared refer in particular to the upper few millimeters of the surface of Mars. Microwave measurements refer to the subsurface, at depths approximately equivalent to ten times the wavelength, assuming there are no sharp boundary layers in the subsurface. The discussion of thermal models in Section 3.1.1 makes it apparent that diurnal thermal

*A mean infrared emissivity ϵ_{20} of 0.90 in the 18 to $25\ \mu$ range was also assumed for the polar cap. This admittedly arbitrary value was selected because of a lack of laboratory measurements on CO_2 frosts in the mid-infrared region.

amplitude must decrease with increasing depth, and thus with increasing wavelength until the depth, ℓ , is reached where the amplitude has decreased to zero.

For further details on the theory of radio emission from a planetary surface, see Piddington and Minnett (1949). They assumed an airless planet and a vertically homogeneous subsurface, with thermal and electrical properties independent of temperature.

Observations

A critical evaluation of all available radio observations of Mars has recently been made by Epstein (1971), taking into account calibration uncertainties and sensitivity of equipment used. (In some cases he recalculated the uncertainties.) By utilizing only the most accurate and reliable observations to date (22 of the 32 data sets examined), Epstein arrived at the plot presented in Fig. 17 of the normalized temperatures T_b' versus wavelength λ . * The error bars plotted are the total uncertainty (1- σ) including the absolute calibration uncertainties.

The disk-averaged brightness temperatures used for the plot are listed in Table 1, both as observed (T_b) and normalized ($T_b' = T_b \cdot C$) to the mean solar distance $r_0 = 1.524$ AU. The normalization factor C (discussed below) was taken as follows:

$$\text{For observations at } \lambda < 1 \text{ cm, } C = (r/r_0)^{1/2}$$

$$\text{For observations at } 1 \text{ cm} \leq \lambda < 10 \text{ cm, } C = (r/r_0)^{1/4}$$

$$\text{For observations at } \lambda \geq 10 \text{ cm, } C = 1$$

The wavelength dependence of this normalization factor, C , was proposed by Morrison, Sagan and Pollack (1969) and discussed by Epstein et al. (1970). The argument is as follows: As depth beneath the surface increases, the subsurface layers are found to be affected less and less by the insolation variations (diurnal and even annual), so that at a depth corresponding to the origin of very long centimeter waves, the temperature remains essentially constant. Therefore, at such depths and corresponding wavelengths, one may take $C = 1$. At intermediate depths and shorter centimeter wavelengths, the temperature may be "scaled approximately as the average of dayside and nightside heliocentric distance corrections," that is between $C = (r/r_0)^{1/2}$ and $C = 1$ respectively. A good approximation to this average is $C = (r/r_0)^{1/4}$. Of course, as Epstein (1971) noted, the wavelength intervals and correction forms are somewhat arbitrary; but the corrections are small for Mars eccentricity (less than $\pm 5\%$ for $C = (r/r_0)^{1/2}$).

*The full details of the evaluation as well as the rejected observations may be found in Epstein's paper.

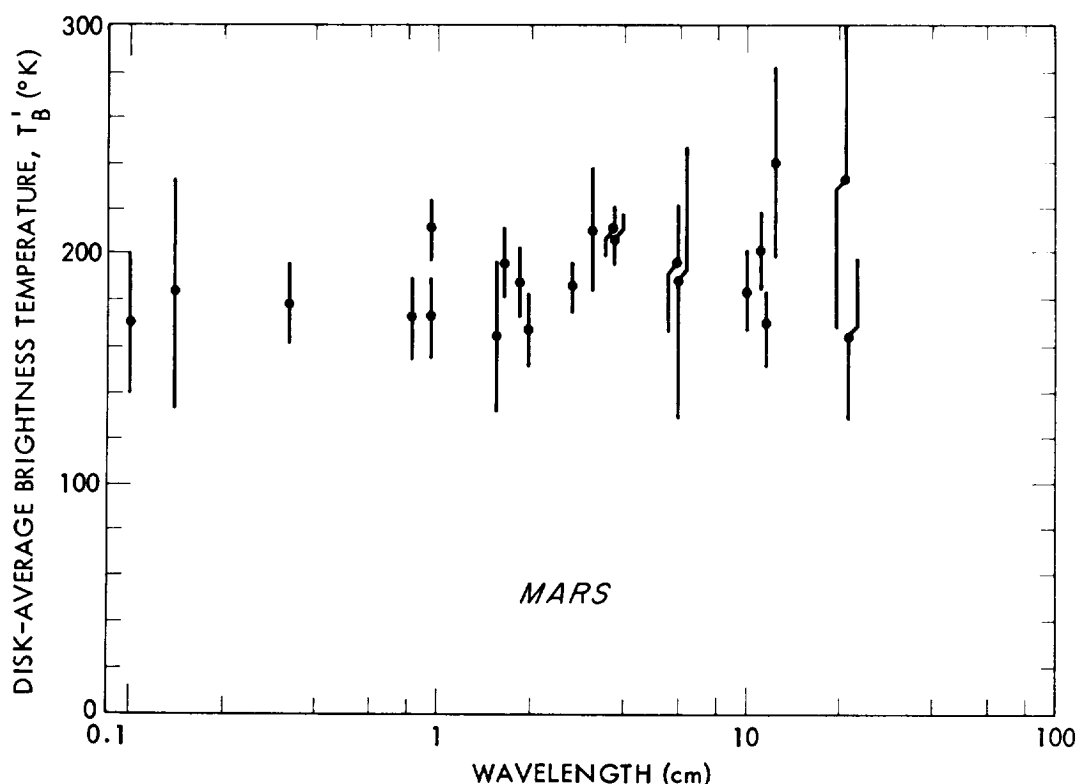


Fig. 17. The radiowave spectrum of Mars, as plotted by Epstein (1971) after initial evaluation of all available observations.

The present picture of the Martian microwave spectrum cannot be considered to be a very accurate one. As usual in radioastronomy measurements (see the lunar case, for example), the measurements of the continuous spectrum are plagued with large error bars associated with individual data points. The sources of these errors are well known: calibration procedures (5-15%), antenna pointing (1-3%), atmospheric attenuation (H_2O) correction (1-3%), etc.; but the determination of the respective amounts of those errors, or uncertainties, is never an easy matter. In the case of the Martian spectrum, calibration has been the dominant problem. At long wavelengths, the Martian flux is weak and difficult to measure (low signal-to-noise ratio); however, good calibration is available from the standard radio sources (usually radio galaxies) with strong, well-measured fluxes. Here the calibration uncertainty may be ~4-5%. At short wavelengths (<2 cm), these radio sources are very weak and have not been accurately measured; therefore, one resorts to the Moon, Sun, or planets for calibration. However, their fluxes are not always stable and well defined, and the calibration uncertainty is large (10-15%). The flux equivalences of all these comparison sources have not always been reliably established. As a result, the Martian spectrum suffers to some unknown extent from internal inconsistency due to the variety of calibration procedures over the 0.1 to 20-cm wavelength range.

Table 1. Disk-averaged brightness temperatures of Mars.

Wavelength, λ (cm)	Observation Date	Brightness Temperature / Disk		Uncertainty (1- σ) (°K)	Calibration Standard(s)	Reference
		Reported, T_b (°K)	Normalized to r_0 $T_b = T_b \cdot C$ (°K)			
0.1	1965	165	171	±31	Moon	Low and Davidson (1965)
0.14	1970	180	184	50	Jupiter	Kostenko et al. (1970)
0.33	1967 and 1969	180	178	18	Sun and antenna parameters	Epstein et al. (1970)
0.822	1969	176	173	18	Jupiter	Kuzmin et al. (1970)
0.95	1969	171	173	18	Jupiter	Pauliny-Toth and Kellerman (1970)
0.95	1967	202	211	14	Various sources	Hobbs et al. (1968) Hobbs and Knapp (1971)
1.55	1967	163	165	33	Jupiter	Hobbs et al. (1968)
1.65	1969	197	197	16	Virgo A	Mayer and McCullough (1971)
1.85	1967	185	187	15	Virgo A	Klein (1971)
1.95	1968 and 1969	168	-	17	Virgo A	Pauliny-Toth and Kellerman (1970)
2.7		185	186	12	Virgo A	Mayer and McCullough (1971)
3.14	1958	211	211	28	Antenna parameter and receiver calibration	Giordmaine et al. (1959) Alsop and Giordmaine (1961)
3.75	1965	202	206	12	Virgo A	Dent et al. (1965)
3.75	1967	206	210	11	Virgo A	Klein (1971)
6.0	1965	192	196	27	Hydra A	Kellermann (1965)
6.0	1965	184	188	60	3C 123, Virgo A and 3C 348	Hughes (1966)
10.0	1963	184	184	18	3C 123	Drake (1970)
11.1	1969	201	201	18	Hydra A	Stankevich (1970)
11.3	1965	170	170	19	Hydra A	Kellermann (1965)
12.5	1965	240	240	42	Various sources	Muhleman and Sato (1965) Muhleman (1970)
21.2	1963 and 1965	233	233	65	Hydra A	Davies and Williams (1966)
21.3	1965	163	163	35	Hydra A	Kellermann (1965)

No statistically significant variations of brightness temperature with Martian phase angle have been detected, even at millimeter wavelengths. At the depths in the Martian subsurface where the radio emission originates, it appears the temperature remains essentially constant (see Dent et al., 1965).

Despite the large scatter in the data, the general trend of T_b^i (see Table 1) appears to be flat over the entire range of wavelengths used. Due to the uncertainty in the absolute calibration of the measurements it is not possible to discern whether or not slight spectral slopes exist, as various theoretical models predict. The mean surface temperature in the microwave is about $190 \pm 10^\circ\text{K}$. This corresponds (assuming an emissivity $\epsilon = 0.90$) to a kinetic temperature of about 210°K , which is in fair agreement with the mean disk temperature obtained from infrared observations. Some investigators have interpreted the lower temperatures at 1 mm as a real discrepancy, and have attempted to formulate models of the Martian subsurface to account for it (for example, Sagan and Veverka, 1971).

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3.2 ULTRAVIOLET, VISIBLE, AND INFRARED PHOTOMETRIC PROPERTIES

DATA SUMMARY

Mars brightness at zero phase (See pages 6-8.)

$$\begin{aligned}
 U(1, 0) &= +0.25 & h(1, 0) &= -2.38 \\
 B(1, 0) &= -0.31 & g(1, 0) &= -2.37 \\
 V(1, 0) &= -1.61 & e(1, 0) &= -2.34
 \end{aligned}$$

Phase Coefficients, mag/deg (See pages 8-9.)

$$\begin{aligned}
 U &= 0.019 & h &= 0.014 \\
 B &= 0.018 & g &= 0.013 \\
 V &= 0.017 & e &= 0.013
 \end{aligned}$$

Geometric Albedo (See pages 9-11.)

$$\begin{aligned}
 p_{\lambda 2500} &\sim 0.12 & p_V &= 0.16 & p_{1.5 \mu} &= 0.28 \\
 p_{\lambda 2750} &\sim 0.07 & p_h &= 0.33 & p_{1.75 \mu} &= 0.28 \\
 p_{\lambda 3000} &\sim 0.06 & p_g &= 0.33 & p_{2.0 \mu} &= 0.23 \\
 p_U &= 0.06 & p_e &= 0.32 & p_{2.25 \mu} &= 0.29 \\
 p_B &= 0.09 & p_{1.25 \mu} &= 0.29 & p_{2.5 \mu} &= 0.26
 \end{aligned}$$

Bolometric Bond Albedo (See page 13.)

$$A_{bol} = 0.26$$

Normal Albedo (See pages 14-15.)

Detailed tables are given in Appendix A. Exact definitions, more detailed tables, and sources of the quantities above (and others) are given in the main body of text.

DISCUSSION

3.2.1 Photometric Nomenclature and Theory

The photometric properties of any celestial body may be divided conveniently into two categories: integrated photometric properties, which are studies of the entire body as a unit; and detailed photometric properties, which are studies of a body on a point-by-point basis. In practice, any remote sensing technique will integrate over a considerable area, but hopefully not so great an area that all details are lost. The Moon is a unique body in being near enough

to the Earth that detailed photometry was attempted nearly 200 years ago, by Schroeter. Mars exhibits a disk two orders of magnitude smaller than the Moon in angular size, even under favorable conditions, and photometric interpretations are further complicated by an atmosphere whose effects are difficult to separate from surface properties. Nevertheless, attempts to separate bright and dark areas of Mars' surface in visual photometric studies were made as early as 1909, while visual integrated photometry goes back to at least 1864. Extensive visual and photographic work was done in the period 1920-1939, especially in Russia and France. Much of this work was important in early attempts to gain a qualitative understanding of Mars, but very little of it meets modern quantitative requirements. A comprehensive discussion of this period has been produced by de Vaucouleurs (1954). Modern quantitative photometry of Mars is performed using various types of electronic detectors (photomultipliers, PbS cells, etc.), but it still presents certain problems. The general nature of these problems will be indicated in succeeding paragraphs.

Care must be taken to differentiate between photometric and radiometric data. Photometric data refers to the response of some particular detector system. The data are convolved with the spectral response of the filters, detectors, etc. By pure definition, "photometric data" are visible data received by the human eye, and "physical photometric units" assume an international spectral luminous efficiency curve for the eye. In astronomy, the word "photometric" is used in the broader sense.

In any astronomical photometric system, values are usually given in magnitudes, based on a logarithmic scale of ancient origin. One magnitude difference is exactly the fifth root of 100 ($\sqrt[5]{100}$) ratio in flux; that is, approximately 2.512. Five magnitudes is exactly a factor of 100, 10 magnitudes a factor of 10,000, and etc. The simple formula relating magnitudes m_a and m_b and fluxes f_a and f_b is

$$\log\left(\frac{f_a}{f_b}\right) = -0.4 (m_a - m_b)$$

The magnitude scale is an inverse system; that is, the brighter the object, the smaller its numerical magnitude. For example, an object brighter than magnitude one may be magnitude zero or have a negative magnitude.

The most common photometric system in use today is the ultraviolet, blue, and visual system (UBV), sometimes with red and (near) infrared (IR) and even longer (JKLMN) wavelength measurements added. The exact system is defined by a set of magnitudes for a group of standard reference stars to which observations with any local system must be transformed. Each passband is approximately fixed in any given photometer by a standard detector-filter combination. Colors are given by magnitude differences between passbands in order of increasing wavelength; e.g., U-B, B-V, V-K. The "effective wavelength" of each passband (the mean wavelength integrated over the passband) is given in Table 1. Zeros of the system have been chosen so that U-B, B-V, and all other "colors" are 0.00 for an unreddened star of spectral type A0 V, and so that passband V agrees in zero point with an older "classic" photometric system. Detailed response curves are given by Johnson and Mitchell (1962), Low and Johnson (1964), and (most accurately) for U, B, and V by Azusienis and Straizys (1966).

Table 1. Effective wavelengths in the UBV system. (Johnson, 1966)

Passband	Wavelength, μ
U	0.36
B	0.44
V	0.55
R	0.70
I	0.90
J	1.25
K	2.20
L	3.4
M	5.0
N	10.2

The UBV system was designed for stellar work. It has broad passbands, making it easy to work with faint objects, and so long as the objects in question have energy distributions similar in form (a blackbody curve), no problems arise. Even in stellar work, a slight variation in the ultraviolet passband from photometer to photometer can cause discrepancies (because of departures from a blackbody at the Balmer discontinuity), as can interstellar reddening. Even differences in observatory altitudes can make data reductions difficult because of varying atmospheric opacity in the U-passband. Transformations from a "local" photometric system to the standard system can be multivalued in the worst cases, causing as much as 0.1-0.2 magnitude differences in supposedly "precise" results. By the time Mars' albedo (reflectivity) has been convolved with the solar spectral irradiance, its spectral radiant exitance looks something like an early B-star with 1.5 magnitudes of interstellar reddening, and inevitably there have been systematic differences of as much as 20% in various UBV measurements of Mars (Young, 1970). A general discussion of broadband photometric systems has been produced by Johnson (1963).

In an attempt to fill basic gaps in photometric data and to overcome some of the difficulties of the UBV system, NASA sponsored a program for multicolor photometry of the planets by Harvard College Observatory personnel during the period 1962-1965. This work utilized 10 narrowband (interference) filters, between 3,150 Å and 10,600 Å, in addition to the UBV system (Young and Irvine, 1967). McCord and coworkers have used up to 52 interference filters and a double-beam photometer to study discrete Martian regions between 3,010 Å and 25,230 Å (McCord and Westphal, 1971; McCord, 1968). Still another modern technique utilizes a scanning spectrometer as a monochromator. Younkin (1966) used such an instrument with a bandpass of 50 Å in his Mars work.

Any photometric system may be converted to a radiometric one by absolute calibration of the photometric system response curve. Either photometric or radiometric values can also be cited in absolute physical units. General discussions of the absolute calibration problem have been offered by Code (1960), Willstrop (1960), and Oke (1965). Numerical values for absolute calibration of the UBV system in all the passbands U through N have been given by Johnson (1966), but these values may be in error by as much as 10% (Azusienis and Straizys, 1966; Young, 1969). The best available calibrations for the U-, B-, and V-passbands have been given by Azusienis and Straizys (1966). For planetary studies, measurement of the absolute spectral exitance may not be required. Mars only emits (as opposed to reflects) significantly in the far infrared. Therefore, various ratios of "flux out" to "flux in" are sufficient to describe the planet's behavior in the shorter wavelengths. Comparison with the Sun is usually made through one or more intermediary standard stars which have been intensively studied and which in turn have been (indirectly) compared to the Sun.

3.2.2 Reflection Versus Emission on Mars

The ratio of reflected to emitted flux, as a function of wavelength at any given location on Mars, is a function of (1) the incident radiant energy (see Section 6); (2) the atmosphere (see Sections 5.3, 5.4, and 6); (3) the local normal albedo (see paragraphs following); (4) the local geometry and emissivity (see Section 3.1); and (5) the local temperature (which, in turn, is determined by a complex interaction of local transport properties and the past history of the radiant field).

The spectral irradiance of the Sun at Mars is better known than the other quantities in question, although there are still uncertainties of at least 1-2% (see Section 6). This model assumes the values given by Thekaekara (1970), which integrate to a total electromagnetic irradiation of 582.7 W m^{-2} at Mars' mean solar distance.

The Martian normal albedo (precisely defined in later paragraphs) is poorly determined in the infrared beyond 2.5μ . However, between 1.0μ and 2.5μ the albedo appears to be about 0.4 for bright areas and 0.15 for dark areas (McCord, Elias, and Westphal, 1971). Sinton (1967) has presented evidence for a large absorption feature at 3.0μ , where the albedo drops to perhaps 0.1 in both regions and then rises back to the previous level at about 4.0μ . The work of Beer, Norton, and Martonchik (1971) confirms this general behavior. There are no published data beyond 4.0μ .

The brightness temperature of a surface is the temperature that a blackbody (a body with relative emissivity of unity) would have to possess in order to emit the same power, at the wavelength of observation, as is actually measured. Remote observations of Mars in the "radiometric window" ($8\text{-}14 \mu$) and at microwave frequencies are often reported as brightness temperatures, since these are directly related to what is actually measured (see Section 3.1). Brightness temperature can be converted to (kinetic) temperature, only if the emissivity is known or assumed.

Figure 1 is a plot of curves of spectral radiant exitance (power emitted per-unit-area and wavelength) versus wavelength for blackbodies of 150°K, 200°K, 250°K, and 300°K, and also curves of the mean solar spectral irradiance times the normal albedo (for typical bright and dark areas). Allowing for the (roughly) cosine effect of nonorthogonal illumination would further reduce the reflected contribution, of course, making the later set of curves the highest possible for the reflected contributions. The normal albedo is assumed constant at the 4 μ value for all longer wavelengths. Somewhere beyond 4 μ the albedo presumably drops, so the assumed values may be too high. It is clear that at wavelengths shorter than about 3.5 μ , reflected energy dominates emitted energy. Beyond 9 μ , emitted energy even dominates reflected energy from the cold, highly reflective, polar caps. The curves do not allow for effects of local geometry or non-isotropy in reflection or emission.

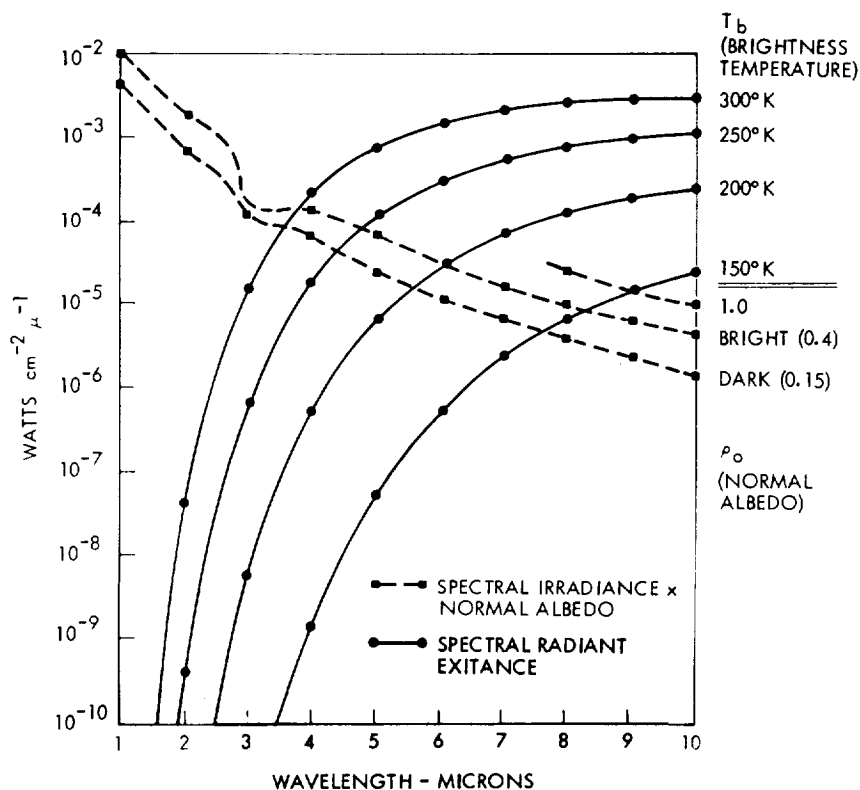


Fig. 1. Reflected solar radiation versus emitted radiation from Mars.

3.2.3 Integrated Photometric Properties

As described previously, Martian photometric properties can be divided into integrated and detailed. The integrated properties are considered first. These include the total brightness, the average color, the variation of brightness and color with phase (the phase function), the Bond (or spherical or Russell-Bond) albedo, and the geometric albedo. All of these vary somewhat with Martian rotation, as various features rotate into the observable hemisphere, and with Martian season, as polar caps grow and shrink and the surface undergoes the "wave of darkening" (see Section 4.2). At shorter wavelengths, additional variable effects (presumably atmospheric) are noted.

Brightness, Opposition Effect, and Color

The body-centered angle between the source of illumination (the Sun) and the observer (detector) is called the phase angle α (see Fig. 2). Where there is need to discriminate, the phase angle is negative before zero phase (opposition). In fact, because the orbits of Earth and Mars are not coplanar, Mars could reach true zero phase, as seen from Earth, only if opposition were to occur when the planet was at an orbital node. The brightness is a nonlinear function of phase. Near zero phase, the planet appears slightly brighter than would be predicted by extrapolation to zero phase of a linear fit to data in the 10° to 30° phase interval. This "enhanced" brightness for phase angles $|\alpha| < 10^\circ$ is called the opposition effect. Actually, the phase curve has a slight continuous upward curvature out to 40° phase, and there is argument whether any effect remains, if a quadratic or cubic fit is used rather than a linear one. (The Moon, on the other hand, has an unquestionably real opposition effect.)

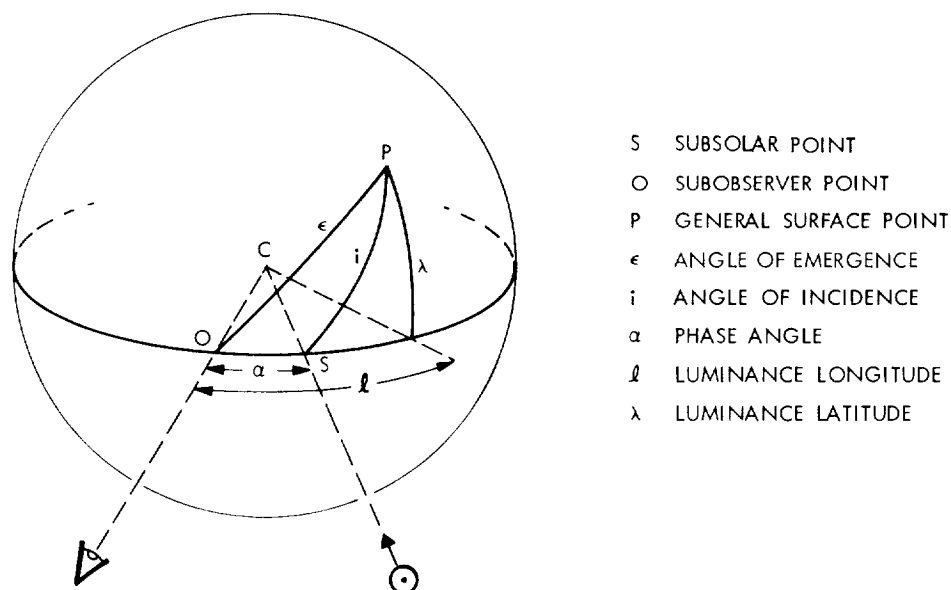


Fig. 2. Photometric coordinates.

Ignoring rotational, seasonal, or secular effects, the mean magnitude of a planet is given by the expression

$$M = M(1, 0) + 5 \log(r d) + \Delta M(\alpha)$$

where

$M(1, 0)$ = mean magnitude at zero phase and at unit distance from Earth and Sun, whether this configuration is physically possible or not. It is a form of absolute magnitude for solar system objects.

r = distance from Earth, in AU

d = distance from Sun, in AU

$\Delta M(\alpha)$ = correction for phase angle α

Because Mars rarely ever approaches true zero phase, it is useful for some purposes to use $M_\ell(1, 0)$ which is the same as $M(1, 0)$ except it is calculated from a linear extrapolation to zero phase from phase data taken for $\alpha > 10^\circ$ and therefore does not include any curvature of the phase function or opposition effect.

The value of $M_\ell(1, 0)$ will appear to vary with rotation, season, etc., depending upon the passband. In general, the variation is greater in the red regions of the spectrum, where more surface detail is apparent, than in the blue regions. In the U- and B-passbands, the variation may be in the order of 0.10 to 0.15 magnitudes (Young, 1970). Typically, in the V-passband there may be 0.15 magnitude variation as a function of central meridian longitude (Young, 1970; de Vaucouleurs, 1970; Irvine et al., 1968a; Irvine et al., 1968b). In the red, the variation increases to about 0.3 magnitudes at $\lambda 7300$, and perhaps 0.35 magnitudes at $\lambda 10600$ (Irvine et al., 1968a; Irvine et al., 1968b).

Any attempt to quote values of $M_\ell(1, 0)$, or worse $M(1, 0)$, must necessarily be restricted to mean values of inhomogeneous data until such time as a program such as Young's, to quantitatively disentangle all of the various effects, is completed. The review article by de Vaucouleurs (1970) effectively covers work at three observatories during the Martian oppositions of 1952, 1954, and 1958. The Harvard work at Le Houga (Irvine et al., 1968a) and Boyden (Irvine et al., 1968b) covers the period from May 1963 through July 1965. The Le Houga results and those reported by de Vaucouleurs are in good agreement, while the Boyden results are consistently fainter in the red regions, and, according to the authors, reflect the presence of more dark markings, as seen from the Boyden station (although it is not obvious that this is the case). This review arbitrarily takes the mean of the extensive Le Houga and Boyden results for use here as follows:

$$\begin{array}{lll} U_\ell(1, 0) = +0.35 & V_\ell(1, 0) = -1.51 & g_\ell(1, 0) = -2.27 \\ B_\ell(1, 0) = -0.21 & h_\ell(1, 0) = -2.28 & e_\ell(1, 0) = -2.24 \end{array}$$

The h, g, and e passbands of the Harvard photometry have effective wavelengths of 7,297 Å, 8,595 Å, and 10,635 Å, respectively.

The Harvard photometry did not disclose any opposition effect. The Le Houga observations included only three sets of observations under 10° phase angle, but the Boyden observations included nine sets under 5° and 18 sets under 10°. O'Leary worked in 1967 and 1969 when the phase angle reached the very favorable small values of 1.2° and 1.3°, respectively (O'Leary, 1967; O'Leary and Jackel, 1970), and generally obtained results which qualitatively supported earlier suggestions of an opposition effect by de Vaucouleurs (1959) and others. The 1969 effect reported was only about half the size of the 1967 effect (and the data appear to be of greater precision). It is suggested here that at visual wavelengths an effect of 0.1 magnitudes should be "added"; that is,

$$M(1, 0) = M_{\phi}(1, 0) - 0.10$$

Perhaps half of this is "true" opposition effect, and the remainder is correction for curvature in the phase curve. Martian photometry is in a sufficiently primitive state that further sophistication seems unjustified at the present time.

As previously noted, colors are given by magnitude differences between two passbands. The colors of Mars compared to those of the Sun (as given by Irvine et al., 1968a) are

<u>Color</u>	<u>Mars</u>	<u>Sun</u>
U-B	0.56	0.14
B-V	1.30	0.65
V-h	0.77	0
V-g	0.76	0
V-e	0.73	0

These figures indicate Mars to be a body much redder than the Sun, which is no great surprise.

Phase Function

The phase function of a body, commonly written $\phi(\alpha)$, describes the flux reflected as a function of phase angle, normalized to zero (full) phase; i. e.,

$$\phi(\alpha) = \frac{F(\alpha)}{F(0)}$$

As always, practical measurements are made in a particular photometric system and, when properly calibrated, can sometimes be transformed to other systems, with only a small loss in accuracy. Plots of $\phi(\alpha)$ for the Moon, Venus, and Mercury often appear with α a polar coordinate. Mars, however, can never be observed from Earth at a phase angle greater than 48°, and, except for the opposition effect, this phase variation can be roughly represented by a linear expression

$$\Delta M(\alpha) = \mu\alpha$$

where the coefficient μ is often called the phase coefficient. In this form, $\Delta M(\alpha)$ must be used with the "linear" absolute magnitudes $M_\phi(1, 0)$ to derive Martian brightness. In theory, additional coefficients and negative powers of α could be included in the expression for $\Delta M(\alpha)$ to represent the opposition effect, but, as noted in previous paragraphs, there is still too much uncertainty about the amount or even the existence of the effect. Ultimately, it is hoped that spacecraft data can be used to extend the phase function to phase angles greater than 48° , but such data are not yet available. The phase coefficients for the various passbands being used in this review are taken from Irvine et al. (1968b), as follows:

<u>Passband</u>	<u>μ mag/deg</u>	<u>Passband</u>	<u>μ mag/deg</u>
U	0.019	h	0.014
B	0.018	g	0.013
V	0.017	e	0.013

Thus, there is a slight change in color with phase, in that Mars appears slightly redder with increasing phase. It must be noted that a comprehensive study of all Martian photometric data by Young* shows a distinct change of B - V with phase but no evidence of any change in U - B.

Geometric Albedo

The geometric albedo p of a body is the ratio of its mean luminance at full phase ($\alpha = 0$) to the luminance of a perfectly diffusing ("intrinsically white") plane surface at the same point and perpendicular to the source of illumination (the Sun). A perfect diffuser is one which scatters 100% of the power incident upon it (absorbing none) according to the Lambert law of cosines. Its luminance appears the same from any angle, and is proportional to the cosine of the angle of incidence. The geometric albedo can be calculated from the expression

$$\log p = 0.4 [M_s - M(1, 0)] - 2 \log R + 16.350$$

where

M_s = apparent magnitude of the Sun at one AU in the photometric band in use

$M(1, 0)$ = planetary absolute magnitude in the photometric band in use (as in previous paragraphs)

R = mean radius of body (in kilometers)

Details of the derivation can be found in Chapter VI of Shorinov (1964) or, in less detail, in Harris (1961).

*Private communication (work to be published).

Geometric albedo is a widely used concept, but it does suffer observational and theoretical inconveniences. The magnitude of the Sun must be known in the relevant photometric system, as the Sun is so bright relative to other objects, there are usually certain inaccuracies in measurement. The zero-phase magnitude of Mars is uncertain because of the opposition effect, as previously discussed. Real bodies in space, such as Mars, are generally more or less spherical. Comparing a planet's hemisphere to a perfectly diffusing plane is rather artificial. Comparison to an intrinsically white body of the same shape would be more illustrative. A perfect Lambert surface would then have an albedo of unity, whereas its geometric albedo is only two-thirds. This should not imply a body can have a geometric albedo no larger than two-thirds. A body with very strong backscattering characteristics (something approaching a perfect retrodirective reflector), can have an indefinitely large geometric albedo.

A V-magnitude for the Sun of -26.8 is adopted here. Various determinations generally report internal errors of perhaps 0.02 magnitude, but differ from each other by far greater amounts. A realistic total probable error may be as much as 0.1 magnitude. Solar magnitudes in the other passbands are obtained by applying the colors previously given. A Martian mean radius of 3383 km is used, and an opposition effect of 0.1 magnitude is arbitrarily applied to all $M_\phi(1,0)$ values. The resulting geometric albedos are

$$p_U = 0.06 \quad p_h = 0.33$$

$$p_B = 0.09 \quad p_g = 0.33$$

$$p_V = 0.16 \quad p_e = 0.32$$

Observations of ultraviolet flux from Mars have been made by Evans (1965) and by Broadfoot and Wallace (1970), using sounding rockets. These results are difficult to calibrate absolutely, as they each refer to one point in time. Evans' work was done with an objective grating, while Broadfoot and Wallace used a slit spectrometer that accepted 42% of the disk area. For purposes of this review, the curve of Evans is "calibrated" by matching it at 3500 Å to the Harvard photometry quoted previously. On this basis, crude geometric albedos can be assigned at a few additional wavelengths, as follows:

$$p_{\lambda 3000} \approx 0.06$$

$$p_{\lambda 2750} \approx 0.07^5$$

$$p_{\lambda 2500} \approx 0.12$$

Barth and Hord (1971) have reported on spectra taken with the Mariner ultraviolet spectrometers. They show an ultraviolet reflectance for a "desert region," which is said to be Meridiani Sinus, actually a dark area (the distinction is not very significant at short wavelengths). In any case, their results refer to a specific point and are impossible to transform to geometric albedos (see succeeding paragraphs on detailed photometry).

Observations of Mars at wavelengths longer than one micron all are fairly recent and are primarily detailed photometry, rather than integrated photometry. McCord and Westphal (1971) have presented integrated disk results for one Martian longitude, centered on Amazonis, with bright areas dominant. Their values, given in Table 2, are taken from Figs. 7 and 8 of McCord and Westphal and refer to a phase angle of 5° . The "corrected values" were derived, by assuming a phase coefficient of 0.013 magnitude per degree and an opposition effect of 0.1 magnitude, in an attempt to make them true geometric albedos. The resulting values at 0.85μ and 1.05μ are slightly smaller than those of the Harvard photometry, but neither bandwidths nor wavelengths are identical, and the absolute accuracy is probably no better than 10% in any event.

There is no absolute integrated photometry beyond 2.5μ . The works of Sinton (1967) and of Beer, Norton, and Martonchik (1971) show evidence of a large decrease in albedo near 3μ and then a rise back to roughly the same level as at shorter wavelengths, but all of this work is on relative scales, and Sinton's work does not refer to the entire disk. In addition, at these wavelengths there are no phase coefficients to be used for correction to zero phase. Therefore, it can only be stated that the geometric albedo appears to drop under 0.1 near 3μ and to rise back over 0.2 from 3.6μ to 4.0μ . Beer* and Norton recently have acquired data beyond 4.0μ , but no results are available at this time.

Table 2. Infrared geometric albedos.

Wavelength (μ)	Geometric Albedo	
	McCord and Westphal	"Corrected Values"
0.855	0.27	0.31 ⁴
1.053	0.27	0.31 ⁴
1.25	0.25	0.29
1.50	0.24	0.28
1.75	0.24	0.28
2.00	0.20	0.23
2.25	0.25	0.29
2.50	0.22	0.26

*Private communication.

Bond Albedo and Phase Integral

The Bond albedo A , often called spherical albedo and sometimes the Russell-Bond albedo, is a quantity with clear physical meaning. It is the ratio of the power (flux) reflected in all directions by a body to the power incident upon it in a collimated beam. It is the fraction of flux incident upon a body that is not absorbed. The geometric albedo is a measure of the flux returned at zero phase. There is a quantity q called the phase integral, that is a measure of scattering at other phases, which relates A and p . It is the ratio of flux scattered in all directions to that scattered at zero phase, per unit solid angle. It can be shown (Sharonov, 1964; Harris, 1961) that

$$A = pq$$

where

$$q = 2 \int_0^\pi \phi(\alpha) \sin \alpha \, d\alpha$$

and $\phi(\alpha)$ is the phase function (converted into intensity units rather than the logarithmic magnitude units) as in previous paragraphs. Phase coefficients vary slowly with color, and therefore q must be a (weak) function of color. Worse, Mars cannot be observed from Earth at $\alpha > 48^\circ$. It has been customary to use Russell's Rule, a 55-year-old empirical relationship Russell found to hold true within $\pm 5\%$ for Mercury, Venus, and the Moon, which states that

$$q \sim 2.2 \phi(50^\circ)$$

Veeverka (1971) has recently shown that this empirical law is the direct consequence of rapid decrease in brightness with increased phase. Using a two-point Gaussian quadrature on the phase integral, he showed that

$$q \sim 2 (1 + \delta) \phi(55^\circ)$$

where $\delta \equiv \frac{\phi(125^\circ)}{\phi(55^\circ)}$ and is a small quantity (~ 0.1). Using actual values of δ and ϕ for Mercury, Venus, and the Moon, the two formulas, Gaussian and Russell's, agree quite well.

Irvine et al. (1968b) derived the following values for the phase integral q , using a version of Russell's Rule, with a constant 2.17 based upon modern data by Harris (1961):

<u>Passband</u>	<u>Phase Integral</u>	<u>Passband</u>	<u>Phase Integral</u>
U	0.92	h	1.12
B	0.94	g	1.17
V	1.01	e	1.20

Corresponding values for the Bond albedo A, using the geometric albedos given on page 10, are as follows:

<u>Passband</u>	<u>Bond Albedo</u>	<u>Passband</u>	<u>Bond Albedo</u>
U	0.05 ⁵	h	0.37
B	0.08 ⁵	g	0.39
V	0.16	e	0.38

Bolometric Bond Albedo

The quantity of importance in energy balance studies is the bolometric Bond albedo, the average albedo weighted by the solar flux $F_{\odot}(\lambda)$.

$$A_{\text{bol}} = \frac{\int_0^{\infty} A(\lambda) F_{\odot}(\lambda) d\lambda}{\int_0^{\infty} F_{\odot}(\lambda) d\lambda}$$

A constant value of $q = 1.2$ has been used with the infrared geometric albedos previously quoted, the values above, and the solar flux values of Section 6 to calculate this integral. A numerical integration from 0.3μ to 2.5μ gives a value of 0.266. The neglected wavelengths less than 0.3μ include 1.2% of the solar flux and are of low albedo. The wavelengths greater than 2.5μ include 3.7% of the solar flux and are low at 3.0μ and high at 4.0μ . Assuming zero albedo for these regions would only reduce the value to 0.253. Therefore,

$$A_{\text{bol}} = 0.26$$

is adopted as the best current value for the bolometric Bond albedo. This is slightly larger than the value of Irvine et al. (1968b), because 0.10 magnitude of opposition effect has been included, the Sun is assumed 0.01 magnitude fainter, and new infrared data have been used. The potential sources of systematic error are such that assignment of a "probable error" makes little sense.

3.2.4 Detailed Photometric Properties

Detailed photometric properties of Mars include brightness and color of localized areas as a function of phase, the normal albedo, the photometric function, the radiance factor, and the radiance coefficient. The disk of Mars is so small, even near opposition, that excellent seeing is required for relatively crude detailed photometry by Earth-based telescopes. Results to date have been limited to a few of the larger dark and bright Martian features and within a limited range of phase angles. Hence, many of these listed detailed properties are simply unknown. They are described here briefly for completeness. Hopefully, the current program of spaceflights to Mars may provide additional answers.

Radiance Coefficient

The radiance coefficient r is defined as the ratio of the radiance observed to that of a white Lambert surface (plane) at the same inclination. The radiance factor ρ is defined as the ratio of the radiance observed to that of a white Lambert surface at zero inclination to the incident illumination. Obviously,

$$\rho = r \cos i$$

In practical observing, the detector will have an irregular passband and the quantities measured are luminances, so they are sometimes assigned the more appropriate adjective, luminance, becoming luminance coefficients and luminance factors.

Radiance Factor, Photometric Function, Normal Albedo, etc.

The radiance factor of an element P on a sphere can be written

$$\rho = \rho_0 f(i, \epsilon, \alpha)$$

where $f(i, \epsilon, \alpha)$ is called the photometric function and is normalized, so that $f(0, 0, 0) = 1$, by ρ_0 which is called the normal albedo. The quantities i , ϵ , and α are the angle of incidence, angle of emergence, and phase angle as previously shown in Fig. 2. The normal albedo then is the exact equivalent in detailed photometry to geometric albedo in integrated photometry; that is, the luminance at zero phase, compared with an intrinsically white plane Lambert surface perpendicular to the source of illumination. It differs only in referring to a point at the center of the disk, rather than to the mean of the entire hemisphere. There is an unfortunate tendency on the part of many recent authors of papers on detailed photometry to use the term geometric albedo for any reflectivity measured at zero phase or reduced to zero phase. This is NOT correct for any body which exhibits detectable limb darkening; i. e., Mars.

There are additional terms in common use in detailed photometry. The phase plane (occasionally phase-angle plane) is the Sun-object-observer plane (see Figs. 2 and 3), and the luminance equator (or radiance equator) is the intersection of the phase plane with the surface under study. The luminance longitude is the angle of observation (reflection angle) projected into the phase plane. Usually, the angle is taken to be negative if it is on the subsolar point side of the subobserver point.

When observing Mars from the Earth, it is perfectly acceptable to consider the phase plane as passing through the center of Mars for all observations (plane SCO in Fig. 2), since the error involved is, at most, a few arc seconds. The luminance equator then becomes the great circle where the phase plane intersects Mars. The relationship between luminance latitude λ and longitude ℓ and the angles previously used (see Fig. 2) is (Harris, 1961)

$$\cos \epsilon = \cos \lambda \cos \ell$$

$$\cos i = \cos \lambda \cos (\ell - \alpha)$$

However, when Mars is observed from a flyby, an orbiter, or a spacecraft on the Martian surface, it is absolutely necessary to use the proper (local) definitions as shown in Fig. 3.

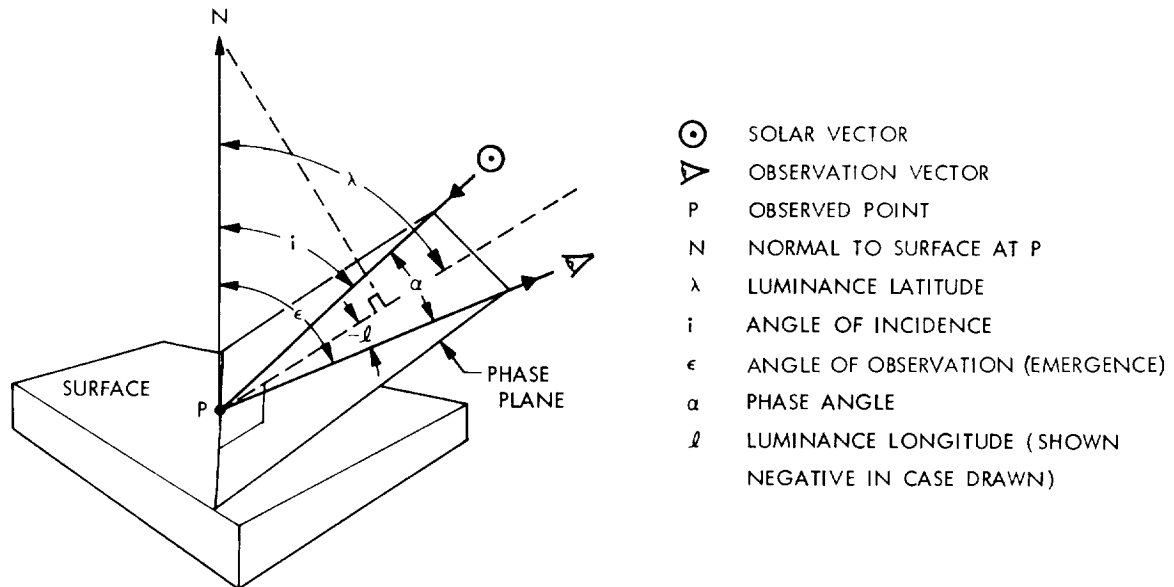


Fig. 3. Local photometric geometry. (after Holt and Rennilson, 1968)

Empirical Photometric Behavior

Most detailed Martian photometry has been indirectly absolute, in the sense that various regions on the disk have been ratioed to one area near the disk center, and that area alone has been compared to the Sun through intermediary standard stars. Modern detectors, amplifiers, and recorders are sufficiently linear and stable in operation, such that system drift is no longer a severe problem. The extinction caused by the Earth's atmosphere does vary strongly with zenith distance, with wavelength, and occasionally in time, however, and continuous reference to standards is necessary to remove these effects in order to obtain absolute results.

The amount of data required for full evaluation of the photometric function for each physiographic unit is quite large and has never been totally obtained. It is not possible to obtain all of the required data from observations on Earth. It has sometimes been assumed that Mars is a Lambert surface (with $\rho = \rho_0 \cos i$), but this is really unacceptable. A Lambert surface has $q = 1.5$, and the phase integral for Mars is clearly much smaller (as stated previously). Young (1969) suggested the use of Minnaert's empirical law for the photometric function. It is a relatively simple law and satisfies the reciprocity principle (stating that light rays should be reversible "through the system" unless there is a

significant amount of polarization). Minnaert's law can provide an excellent fit to lunar data (Harris, 1961), even though the Moon does exhibit some polarization. The law has the form

$$\rho \cos \epsilon = C(\alpha) [\cos i \cos \epsilon]^{K(\alpha)}$$

where C and K are functions only of phase angle α for a given passband, and the other quantities are as given previously. For K equal to unity and constant C , this reduces to the Lambert law. Qualitatively, the K is a measure of limb-darkening, and the C is a measure of reflectivity. When $\alpha = i = \epsilon = 0$, then C reduces to the normal albedo. The law is commonly written as a function of luminance, but this differs from the luminance factor only by the amount of the solar illuminance, a constant at any given distance from the Sun.

Results of Detailed Martian Photometry

Young and Collins (1971) used the Minnaert law to reduce data from the far-encounter pictures of Mariners 6 and 7. The data, all taken near a phase angle of 22° , resulted in quite sensibly linear plots of $\log(\rho \cos \epsilon)$ versus $\log(\cos i \cos \epsilon)$ for each of a number of individual Martian features, indicating the Minnaert law to be a good one. There were differences in the results of the two Mariners, however, indicating calibration difficulties. Reference should be made to the Young and Collins (1971) article for the quantitative results.

Binder and Jones (1972) carried out an extensive program of Martian photometry during the 1969 opposition. Lacking sufficient data to derive a complete photometric function without some mathematical framework, they too chose to use the Minnaert formalism to display their results, which give the most extensive detailed coverage of the Martian surface yet attempted by modern means. They utilized a 10-channel spectrophotometer with medium-width passbands, centered upon wavelengths from 0.595μ to 2.270μ . Results were obtained for four phase angles (7.2° , 10.3° , 17.7° , and 18.5°) and for 156 different points on the disk. Binder and Jones' data fit into the Minnaert law very nicely and give evidence that the Minnaert parameter K varies linearly with phase angle and with wavelength over a wide range of values of these quantities, making extrapolations beyond the observations conceivable, though not desirable. Having no observations near zero phase, it was not possible for them to discuss any opposition effect, of course. In fact, lack of opportunity to obtain sufficient reference to standards made it impossible to obtain a normal albedo map. Good data were obtained at 10.3° phase angle. Figure 4 is a plot of "reference albedo" (the average of the albedo at 1.04μ and 1.24μ at 10.3° phase) taken from Binder and Jones (1972). They suggest that the true normal albedos should be 10-15% larger. Binder and Jones data seem sufficiently important that the "spectral albedos" (luminance factors at 10.3° phase) for each of their 10 passbands are listed in Appendix A for 150 observed points.

Binder and Jones (1972) found that their reference albedos tended to cluster around two values, 17% and 35%. Ratios of albedos at different wavelengths, a direct measure of color, also tended to fall into two groups, one associated with each albedo group. This is a quantitative measure of the obvious division of Mars into bright and dark areas. Binder and Jones (1972) also made

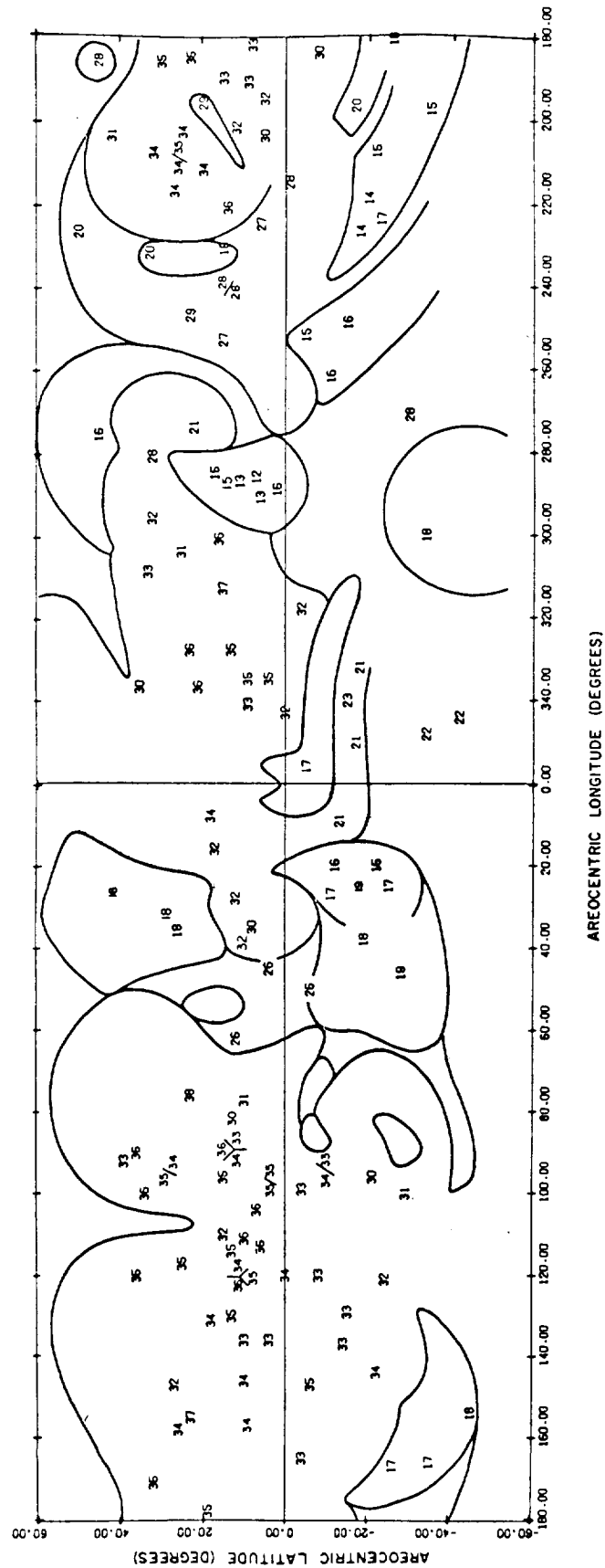


Fig. 4. Reference albedo (the average of the albedo at $1.04\ \mu$ and $1.24\ \mu$ at 10.3° phase) taken from Binder and Jones (1972).

South Polar Cap measurements in six areas. These showed infrared albedos as low as the dark areas. They suggest these may have been caused by the large values of i and e at which they had to observe, or perhaps by "contamination" from underlying or surrounding dark areas.

McCord and Westphal (1971) intercompared seven areas of Mars at 52 wavelengths from $0.30\ \mu$ to $2.52\ \mu$. Their work is well standardized but covers an insufficient range of phase angles to give any information on the photometric function. Their results, showing "geometric albedo" (actually the radiance factor at 5° phase) versus wavelength, shows the full range of Martian reflectivity from darkest Syrtis Major to brightest Arabia, and is reproduced here as Fig. 5.

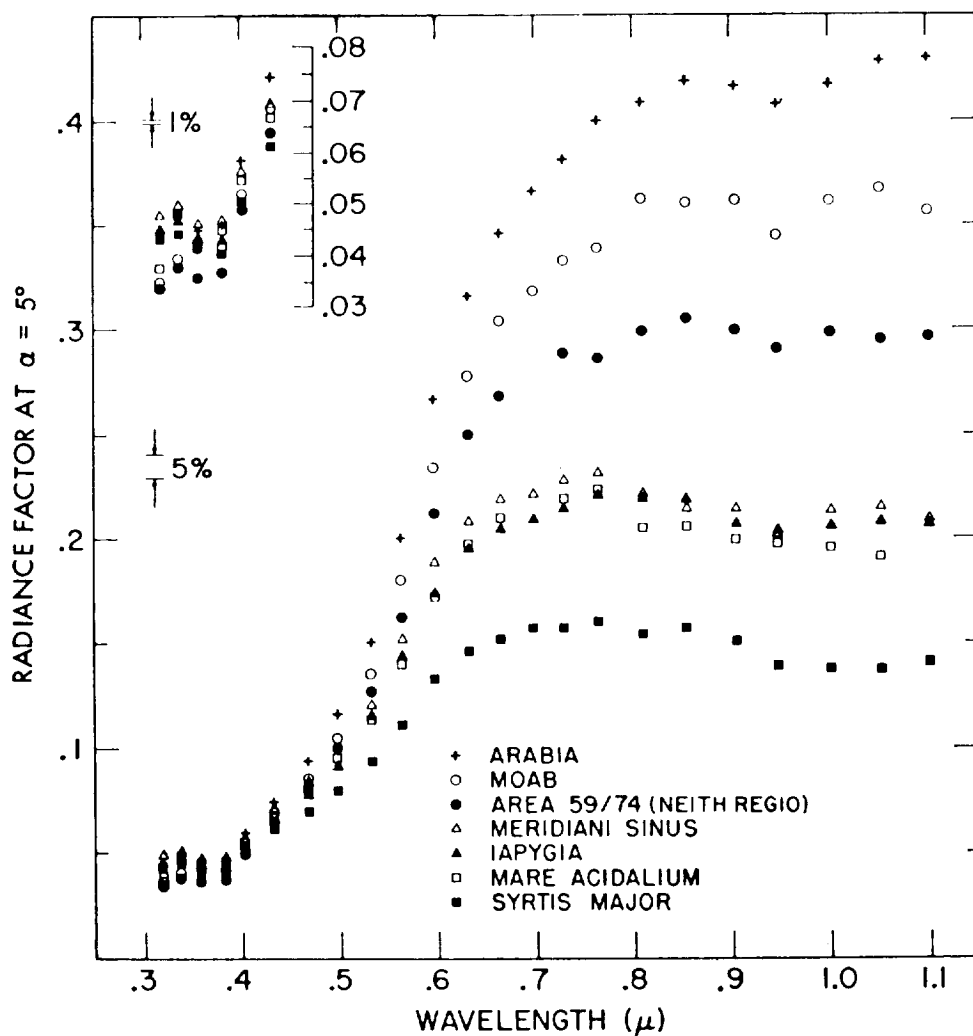


Fig. 5. Spectral radiance factor at 5° phase for seven Martian areas (from McCord and Westphal, 1971). The insert at the upper left shows the ultraviolet parts of the curves on an expanded scale.

O'Leary and Jackel (1970) made scans of Mars at very small phase angles ($1.3^\circ \leq \alpha \leq 3.5^\circ$) in 1969. These seemed to indicate a greater opposition effect for dark Syrtis Major than for bright Arabia.

Barth and Hord (1971), reporting on Mariner Ultraviolet Spectrometer results, were unable to present useful ultraviolet albedos because they lacked comparison spectra of the Sun. They were able to compare the South Polar Cap to the Argyre I desert region under virtually identical photometric conditions, finding the polar cap three times as bright at 2000 Å and 2800 Å and about twice as bright at 2500 Å. Barth and Hord suggest that the Martian surface has an extremely low normal albedo in the ultraviolet except for the polar caps, and that the observed radiation at these wavelengths is mostly scattered by the atmosphere (except over the poles). With this assumption, there should be a direct correspondence between ultraviolet intensity and atmospheric pressure, and, therefore, topography. In fact, a good correlation exists between ultraviolet topography and the Mariner infrared spectrometer topographic results.

3.2.5 General Photometric Conclusions

It is very difficult to do accurate detailed absolute photometry of an angularly small body such as Mars. A large amount of pioneering in visual and photographic photometry (not discussed here) served to provide a qualitative indication of many interesting Martian problems, but it is generally worthless quantitatively. Even the best modern photoelectric work, as discussed in preceding paragraphs, has not been totally adequate, mostly because no individual worker has taken data over a sufficient time span to obtain adequate phase-angle coverage, even for a "static" planet. There is no acceptable quantitative measure of the many supposed dynamic effects, such as the seasonal "wave of darkening." The many classic attempts, to compare changes in dark to bright areas as a function of season, have not proven which area is changing or whether both areas may change. Furthermore, such studies often did not prove whether the changes were true seasonal changes or photometric anomalies. Hopefully, the combined efforts of spacecraft and modern ground-based systems will rectify our lack of knowledge, although a very long-lived spacecraft will be needed.

Both integrated and detailed photometry of Mars have been presented in this section, with little reference to surface or atmosphere. Young (1969) has estimated the Martian atmospheric extinction at about 3% near $\lambda 6000$, and Barth and Hord (1971) find it rising to 10% at $\lambda 3050$. The photometry in visible and infrared wavelengths therefore refers to the surface, except possibly near the limbs. Martian photometry primarily refers to the atmosphere only in the ultraviolet, where surface albedo becomes very small while extinction rises.

One result is conclusive, Mars is a very RED planet in visible wavelengths. Even the dark areas which are often described as predominantly green or greenish-grey, are in fact red, having much higher reflectivity at wavelengths of 6000 Å and longer than at wavelengths of 5000 Å and less. The dark areas are less red than the bright areas, but are nonetheless red. They appear "greenish" to the eye, principally because of visual effects such as the "color-brightness" effect, which makes "areas darker than the average brightness

appear in a contrast color to the illuminant" (Schmidt, 1959). Astronomical photographic exposures are relatively long, and there is reciprocity failure of the red layer of color film, causing it to lose sensitivity relative to the blue and green layers. The result of this is to flatten the apparent spectral reflectivity curve of a dark area. A bright area is also affected, but it retains enough red to simply make it appear more yellow than is realistic. In many color prints, the dark areas appear sufficiently dark that they show little color of any kind (often due to contrast exaggeration through repeated re-copying).

No attempt has been made in this section to discuss the several subtle spectral features caused by the Martian surface materials or to interpret the reported photometric results. These topics are covered in Sections 3.4 and 3.5. Martian infrared and radio emission properties are covered in Section 3.1.

3.2.6 Polarimetric Nomenclature and Results

Introduction to Polarimetry

Astronomical polarimetry has not been a popular field of research, and Martian polarimetry has been no exception. It might best be described as a field of unrealized overexpectations. Polarimetry promises (and delivers) more than simple total intensity photometry, but cannot be expected to produce chemical analyses of solids. Polarimetry can offer insights into particle size and can furnish indices of refraction (when a sufficient range of phase angles is covered). It can "cast the deciding vote in a close race," but cannot by itself furnish unambiguous statements, for example, about composition.

Planetary polarimetry was pioneered in France in the early 1920's by Lyot, and has been carried on assiduously in that country by his pupil Dollfus and coworkers. In fact, the majority of all polarization studies of Mars ever carried out anywhere have been those of Dollfus and Focas in France. Other work has included that of Morozhenko in Russia, and Gehrels, Hall, and Ingersoll in the United States.

A complete description of monochromatic polarized light requires four parameters, those of Stokes being commonly chosen (see Shurcliff, 1962). However, in common astronomical practice at optical wavelengths, all four parameters are not measured. Normally, the maximum intensity $I_{\max}$ (in the plane containing the electric vector and the direction of propagation), the minimum intensity $I_{\min}$ (perpendicular to that plane), and, sometimes, the orientation of the electric vector (or magnetic vector) are measured. These measurements are used to derive a quantity called the degree of polarization V , defined as follows:

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

or, more commonly, the percent of polarization P :

$$P = 100 V$$

and, sometimes, the permil of polarization, written ‰ and defined as 10 P. Some of the techniques used for these measurements have been described by Hiltner (1962) and Gehrels and Teska (1960). A typical paper may then include as little as the percent of polarization, as a function of phase angle in some specified passband and location on the source, or as much as the percent of polarization, the total intensity ($I_{\max} + I_{\min}$), and the orientation of the electric vector at many wavelengths and phase angles for many different locations on the object under study. When the component of the electric vector perpendicular to the phase plane is the larger, polarization is said to be positive. When the component in the phase plane is larger, the polarization is negative. The theory has been developed by Fymat and Abhyankar (1970) for an accurate interferometric determination of the complete Stokes vector (all four Stokes parameters) at very high spectral resolution. A polarimetric observing program of Venus is now being attempted by scientists at the University of Arizona.

Unfortunately, there is no complete "direct" theory of the interaction of light with a complex real surface; only a theory of interaction with smooth, homogeneous surfaces such as optical elements. The "inverse" problem, observing polarized radiation and attempting to derive the nature of the surface from which it was scattered, has not been solved. Attempts to interpret observations of Mars have been strictly empirical, a process of comparing planetary observations to observations of laboratory samples.

At shorter wavelengths, there is a contribution to polarization from the atmosphere. Much early work assumed a pure Rayleigh atmosphere (a pure molecular scattering atmosphere) and made attempts to derive the total atmospheric abundance. These attempts failed for many reasons (see Sec. 5.2; Chamberlain and Hunten 1965; Coulson, 1969). More recent work has been largely at wavelengths near 6000 Å or longer, in an attempt to model surface particle size and composition (see Section 3.4).

Observations

The general polarimetric behavior of Mars can be summarized fairly simply. At small phase angles, polarization is negative, reaching about -1.0% near 12° phase. The inversion angle (the phase angle at which polarization goes from negative to positive) is between 24° and 30°, and polarization reaches +2% between 40° and 45° and apparently continues rising (Dollfus and Focas, 1969). In general, the dark surface areas are more highly polarized than the bright areas, following the "Umov effect," which states that, for materials in general, the degree of polarization is an inverse function of normal albedo. The dark markings appear to show a decrease in polarization during Spring and early Summer (Focas, 1961). Clouds sometimes appear to cause polarization effects (see Section 4.1 and Dollfus, 1961). A more complete review of the observational data has been given by Pollack and Sagan (1969).

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APPENDIX A

MARTIAN ALBEDOS

This appendix identifies the albedos of 150 Martian mare and desert areas at 10 different wavelengths and at 10.3° phase angle, as determined by Binder and Jones (1972). Figure A-1 indicates the areas observed. The numbers contained in Fig. A-1 are not consecutively complete, as some were deleted during the data reduction process. Detailed results for each number-identified area are contained in Table A-1. The entries for each numbered area identify latitude and longitude in degrees, and albedo in percent. Entries prefixed with D are estimated errors, in degrees for latitude and longitude, and in percent for albedo. The results for each area entry are correlated to the 10 wavelengths utilized. The coordinates change with wavelength because of terrestrial atmospheric dispersion. In a few cases, this caused an anomalous albedo curve by moving the infrared observations onto a different physiographic unit. Most points near such boundaries were rejected by Binder and Jones during the data reduction, however.

We are particularly grateful to the authors (A. B. Binder and J. C. Jones) for sending us this important material prior to publication.

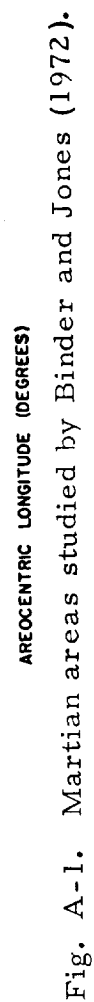


Fig. A-1. Martian areas studied by Binder and Jones (1972).

Table A-1. Martian albedo

		WAVELENGTH									
		.60	.64	.70	.89	1.04	1.24	1.61	1.74	2.14	2.27
NUMBER 2	LATITUDE	9.0	9.7	10.6	11.9	12.5	13.1	13.5	13.7	13.9	13.9
	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	39.0	38.6	38.1	37.3	36.9	36.6	36.3	36.2	36.1	36.0
	DLONGITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	ALBEDO	18.2	23.2	27.7	29.8	31.8	31.9	33.2	36.1	30.4	31.8
	DALBEDO	.6	.5	.4	.4	.4	.5	.4	.5	.7	1.0
NUMBER 3	LATITUDE	12.0	12.7	13.6	14.9	15.5	16.1	16.6	16.8	16.9	17.0
	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	26.0	27.5	27.0	26.1	25.7	25.3	25.0	24.9	24.8	24.7
	DLONGITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	ALBEDO	17.8	22.4	27.1	29.1	31.2	31.2	33.1	35.7	30.9	32.9
	DALBEDO	.5	.7	.6	.6	.7	.8	.9	1.0	1.1	1.7
NUMBER 4	LATITUDE	16.3	17.6	18.5	19.8	20.5	21.1	21.6	21.8	21.9	22.0
	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	15.9	15.4	14.7	13.7	13.2	12.7	12.3	12.2	12.0	12.0
	DLONGITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	ALBEDO	17.6	22.0	26.7	29.0	31.9	31.8	33.6	36.8	31.3	32.5
	DALBEDO	.8	1.0	1.2	1.3	1.5	1.5	1.6	1.8	1.8	1.9
NUMBER 5	LATITUDE	-12.7	-12.0	-11.0	-9.7	-9.0	-8.4	-7.9	-7.7	-7.6	-7.5
	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	8.9	8.5	8.1	7.4	7.1	6.8	6.5	6.5	6.4	6.3
	DLONGITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	ALBEDO	14.6	16.8	19.4	20.1	21.0	20.8	21.4	23.1	18.3	19.1
	DALBEDO	.9	1.0	1.2	1.1	1.1	1.2	1.2	1.3	1.4	1.4
NUMBER 8	LATITUDE	41.0	41.9	43.2	45.0	45.9	46.7	47.4	47.6	47.9	48.0
	DLATITUDE	3.7	3.7	3.8	3.9	3.9	4.0	4.0	4.0	4.0	4.1
	LONGITUDE	26.9	26.2	25.2	23.7	22.9	22.2	21.6	21.3	21.1	21.0
	DLONGITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	ALBEDO	14.2	15.9	18.3	17.7	17.8	16.8	15.8	16.5	13.6	13.2
	DALBEDO	1.0	1.0	1.3	1.4	1.4	1.4	1.4	1.5	1.3	1.5
NUMBER 9	LATITUDE	41.0	42.0	43.2	45.0	46.0	46.8	47.5	47.8	48.0	48.1
	DLATITUDE	3.7	3.7	3.8	3.9	3.9	4.0	4.0	4.0	4.1	4.1
	LONGITUDE	26.9	26.2	25.2	23.7	22.9	22.2	21.5	21.3	21.0	20.9
	DLONGITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	ALBEDO	13.4	15.6	18.2	17.4	17.5	16.3	15.7	16.5	13.4	13.4
	DALBEDO	1.0	1.0	1.3	1.4	1.4	1.4	1.4	1.5	1.4	1.6
NUMBER 10	LATITUDE	8.9	9.8	10.6	12.3	13.0	13.7	14.2	14.4	14.6	14.7
	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	39.0	38.7	38.3	37.7	37.4	37.1	36.9	36.8	36.7	36.7
	DLONGITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	ALBEDO	17.9	22.5	27.1	29.4	31.2	31.3	32.9	34.7	29.2	31.2
	DALBEDO	.6	.5	.6	.5	.6	.7	.7	.9	.9	1.0
NUMBER 11	LATITUDE	27.9	28.8	29.9	31.5	32.4	33.1	33.7	33.9	34.1	34.3
	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	31.8	31.3	30.7	29.8	29.3	28.8	28.5	28.3	28.2	28.1
	DLONGITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	ALBEDO	14.3	16.5	18.5	18.0	18.3	17.1	16.3	17.1	12.9	15.0
	DALBEDO	.8	.8	.8	.9	1.0	1.1	1.3	1.4	1.2	1.3
NUMBER 12	LATITUDE	28.0	28.9	30.1	31.7	32.6	33.3	34.0	34.2	34.4	34.5
	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	32.0	31.5	30.9	30.0	29.5	29.0	28.6	28.5	28.4	28.3
	DLONGITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	ALBEDO	14.2	17.0	19.2	19.0	19.1	17.9	17.0	17.9	14.2	14.3
	DALBEDO	1.1	.8	.8	.9	.9	.9	.9	1.0	1.0	.9

Table A-1. Martian albedo (continued)

		WAVELENGTH									
		.60	.64	.70	.89	1.04	1.24	1.61	1.74	2.14	2.27
NUMBER 13	LATITUDE	-11.1	-10.2	-9.1	-7.5	-6.7	-6.1	-5.5	-5.3	-5.1	-5.0
	DLATITUDE	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
	LONGITUDE	27.1	26.9	26.6	26.2	26.0	25.8	25.7	25.6	25.6	25.5
	DLONGITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	ALBEDO	13.3	15.2	16.7	16.5	16.7	16.6	17.3	18.3	15.5	15.5
	DALBEDO	1.1	.8	1.1	.8	.8	.7	.8	.8	.8	.9
NUMBER 14	LATITUDE	-24.9	-23.9	-22.7	-20.9	-20.0	-19.2	-18.6	-18.4	-18.2	-18.1
	DLATITUDE	3.5	3.5	3.4	3.4	3.3	3.3	3.3	3.3	3.3	3.3
	LONGITUDE	24.9	24.9	24.8	24.6	24.5	24.5	24.4	24.4	24.3	24.3
	DLONGITUDE	3.9	3.9	3.8	3.8	3.8	3.7	3.7	3.7	3.7	3.7
	ALBEDO	12.6	15.2	16.9	16.8	16.7	16.9	17.6	18.3	15.5	15.9
	DALBEDO	1.2	1.2	1.3	1.3	1.2	1.2	1.2	1.3	1.2	1.2
NUMBER 16	LATITUDE	8.9	9.9	11.0	12.7	13.6	14.3	15.0	15.2	15.4	15.5
	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	39.0	38.7	38.4	37.9	37.7	37.5	37.3	37.2	37.2	37.1
	DLONGITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	ALBEDO	17.6	22.5	26.8	28.8	30.8	31.0	32.9	35.5	29.8	31.4
	DALBEDO	.7	.8	.7	.9	.9	.9	1.0	1.2	1.1	1.3
NUMBER 17	LATITUDE	-19.1	-18.0	-16.7	-14.8	-13.9	-13.1	-12.4	-12.2	-12.0	-11.9
	DLATITUDE	3.3	3.3	3.2	3.2	3.2	3.2	3.2	3.2	3.1	3.1
	LONGITUDE	38.1	38.0	37.9	37.7	37.6	37.6	37.5	37.5	37.4	37.4
	DLONGITUDE	3.5	3.5	3.4	3.4	3.4	3.4	3.4	3.4	3.3	3.3
	ALBEDO	12.8	15.5	17.1	16.8	17.3	17.5	18.4	19.5	15.9	17.0
	DALBEDO	1.0	1.0	1.1	.9	.8	.8	.8	.9	.9	1.3
NUMBER 19	LATITUDE	22.9	24.0	25.3	27.3	28.3	29.2	30.0	30.2	30.5	30.6
	DLATITUDE	3.1	3.2	3.2	3.2	3.3	3.3	3.3	3.3	3.3	3.3
	LONGITUDE	76.1	76.1	76.1	76.1	76.1	76.1	76.1	76.2	76.2	76.2
	DLONGITUDE	3.3	3.3	3.3	3.4	3.4	3.4	3.4	3.4	3.4	3.4
	ALBEDO	20.3	25.7	31.2	34.5	36.9	37.3	38.8	41.7	35.6	36.0
	DALBEDO	.8	.8	1.1	1.3	1.5	1.6	1.8	2.3	2.2	2.0
NUMBER 21	LATITUDE	8.9	10.0	11.3	13.3	14.3	15.1	15.9	16.1	16.4	16.5
	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	39.0	38.8	38.6	38.2	38.0	37.8	37.6	37.6	37.5	37.5
	DLONGITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	ALBEDO	18.2	23.3	27.9	30.2	32.0	32.2	33.2	35.7	30.2	30.3
	DALBEDO	.7	.9	1.2	1.1	1.2	1.3	1.4	1.5	1.5	1.5
NUMBER 22	LATITUDE	23.0	23.5	24.1	25.0	25.4	25.8	26.1	26.2	26.3	26.4
	DLATITUDE	3.1	3.1	3.1	3.1	3.2	3.2	3.2	3.2	3.2	3.2
	LONGITUDE	247.0	246.0	244.7	242.9	241.9	241.1	240.3	240.1	239.8	239.7
	DLONGITUDE	3.4	3.5	3.5	3.6	3.6	3.7	3.7	3.7	3.7	3.7
	ALBEDO	17.5	21.1	24.6	26.6	28.0	28.2	29.0	29.6	26.7	27.2
	DALBEDO	.7	.9	1.1	1.3	1.4	1.5	1.6	1.7	1.7	2.0
NUMBER 23	LATITUDE	15.0	15.5	16.1	16.9	17.3	17.7	18.0	18.1	18.2	18.2
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.1	3.1	3.1
	LONGITUDE	240.0	239.0	237.8	235.9	235.0	234.1	233.4	233.1	232.9	232.8
	DLONGITUDE	3.6	3.6	3.7	3.8	3.9	3.9	4.0	4.0	4.0	4.0
	ALBEDO	17.0	20.5	24.2	25.9	27.6	27.9	29.0	29.9	27.1	28.3
	DALBEDO	.9	1.1	1.4	1.6	1.8	1.9	2.0	2.2	2.0	2.2
NUMBER 24	LATITUDE	14.9	15.4	16.0	16.9	17.3	17.7	18.0	18.1	18.2	18.3
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.1	3.1	3.1
	LONGITUDE	253.0	252.1	251.1	249.5	248.7	248.0	247.4	247.2	247.0	246.9
	DLONGITUDE	3.2	3.3	3.3	3.3	3.4	3.4	3.4	3.4	3.4	3.4
	ALBEDO	17.5	20.9	24.2	25.4	26.5	26.3	26.9	27.8	24.2	25.1
	DALBEDO	.5	.7	.8	1.0	1.1	1.1	1.1	1.3	1.2	1.2

Table A-1. Martian albedo (continued)

		WAVELENGTH									
		.60	.64	.70	.89	1.04	1.24	1.61	1.74	2.14	2.27
NUMBER 25	LATITUDE	16.9	17.5	18.2	19.2	19.7	20.1	20.5	20.6	20.7	20.8
	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	265.1	264.4	263.5	262.3	261.6	261.1	260.6	260.4	260.3	260.2
	DLONGITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	ALBEDO	10.9	12.7	14.2	13.6	14.1	14.3	15.6	16.3	13.3	13.7
	DALBEDO	.4	.3	.3	.3	.2	.3	.2	.5	.4	.7
NUMBER 26	LATITUDE	-4.9	-4.4	-3.8	-2.8	-2.4	-2.0	-1.7	-1.5	-1.4	-1.4
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	252.0	251.2	250.3	249.0	248.4	247.8	247.3	247.1	246.9	246.8
	DLONGITUDE	3.4	3.4	3.4	3.4	3.5	3.5	3.5	3.5	3.5	3.5
	ALBEDO	11.8	13.7	15.9	14.7	15.0	15.0	15.5	16.1	13.8	14.6
	DALBEDO	.6	.6	.7	.7	.6	.7	.7	.7	.8	1.0
NUMBER 27	LATITUDE	-11.0	-10.4	-9.7	-8.8	-8.3	-7.8	-7.5	-7.3	-7.2	-7.2
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	262.0	261.4	260.6	259.4	258.8	258.3	257.9	257.7	257.6	257.5
	DLONGITUDE	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
	ALBEDO	11.6	13.8	15.5	15.2	15.3	15.5	16.2	16.6	14.9	16.4
	DALBEDO	.4	.5	.5	.6	.5	.5	.6	.6	.7	1.2
NUMBER 28	LATITUDE	-15.0	-14.4	-13.8	-12.8	-12.3	-11.8	-11.5	-11.4	-11.2	-11.2
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	249.0	248.4	247.5	246.4	245.7	245.2	244.8	244.6	244.4	244.4
	DLONGITUDE	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
	ALBEDO	11.9	13.6	15.5	14.6	15.0	15.3	16.1	16.6	14.2	16.7
	DALBEDO	.8	.9	1.1	1.1	1.1	1.1	1.2	1.4	1.1	1.7
NUMBER 29	LATITUDE	-29.9	-29.2	-28.4	-27.2	-26.5	-26.0	-25.6	-25.4	-25.3	-25.2
	DLATITUDE	3.8	3.7	3.7	3.7	3.6	3.6	3.6	3.6	3.6	3.6
	LONGITUDE	270.8	270.2	269.4	268.3	267.8	267.3	266.9	266.8	266.7	266.6
	DLONGITUDE	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
	ALBEDO	13.6	18.3	23.5	25.7	27.1	27.3	27.9	29.6	26.7	29.6
	DALBEDO	1.3	1.7	2.0	2.2	2.3	2.3	2.2	2.5	2.5	2.6
NUMBER 30	LATITUDE	21.9	22.5	23.3	24.4	24.9	25.4	25.8	25.9	26.0	26.1
	DLATITUDE	3.1	3.1	3.1	3.1	3.1	3.2	3.2	3.2	3.2	3.2
	LONGITUDE	273.9	273.3	272.4	271.2	270.6	270.1	269.6	269.4	269.3	269.2
	DLONGITUDE	3.1	3.2	3.2	3.2	3.2	3.2	3.3	3.3	3.3	3.3
	ALBEDO	14.0	16.7	19.6	20.0	20.9	21.0	21.8	23.6	20.3	22.4
	DALBEDO	.6	.4	.6	.7	.9	.9	.9	1.0	1.0	1.5
NUMBER 31	LATITUDE	32.0	32.6	33.4	34.6	35.2	35.7	36.2	36.3	36.5	36.6
	DLATITUDE	3.3	3.3	3.3	3.4	3.4	3.4	3.4	3.4	3.4	3.4
	LONGITUDE	280.9	280.2	279.3	278.1	277.4	276.9	276.4	276.2	276.0	275.9
	DLONGITUDE	3.3	3.3	3.3	3.4	3.4	3.4	3.5	3.5	3.5	3.5
	ALBEDO	17.5	21.1	25.1	26.3	27.5	27.5	28.3	30.1	25.3	27.4
	DALBEDO	.8	.8	.9	1.1	1.1	1.2	1.3	1.3	1.4	1.3
NUMBER 32	LATITUDE	15.0	15.6	16.4	17.5	18.0	18.5	18.9	19.0	19.2	19.3
	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	287.0	286.5	285.8	284.8	284.3	283.8	283.5	283.3	283.2	283.1
	DLONGITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	ALBEDO	10.6	12.6	14.2	13.6	14.1	14.5	15.9	17.0	14.0	14.9
	DALBEDO	.5	.5	.3	.4	.4	.3	.4	.4	.6	.8
NUMBER 33	LATITUDE	7.0	7.6	8.4	9.5	10.0	10.5	10.9	11.1	11.2	11.3
	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	286.0	285.5	284.3	283.9	283.4	283.0	282.7	282.5	282.4	282.4
	DLONGITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	ALBEDO	9.6	11.9	13.0	11.6	11.5	11.4	12.2	12.8	10.7	11.0
	DALBEDO	.3	.2	.2	.2	.2	.2	.3	.2	.3	.6

Table A-1. Martian albedo (continued)

		WAVELENGTH									
		.60	.64	.70	.89	1.04	1.24	1.61	1.74	2.14	2.27
NUMBER 34	LATITUDE	-33.9	-33.0	-32.0	-30.5	-29.8	-29.2	-28.6	-28.5	-28.3	-28.2
	DLATITUDE	4.0	4.0	3.9	3.8	3.8	3.7	3.7	3.7	3.7	3.7
	LONGITUDE	300.5	299.8	298.9	297.7	297.1	296.6	296.2	296.0	295.9	295.8
	DLONGITUDE	4.1	4.0	4.0	3.9	3.8	3.8	3.8	3.7	3.7	3.7
	ALBEDO	13.4	15.8	17.9	17.1	17.7	17.3	17.7	18.9	15.3	17.2
	DALBEDO	1.2	1.3	1.3	1.2	1.2	1.1	1.1	1.2	1.1	1.2
NUMBER 35	LATITUDE	45.0	45.8	46.8	48.2	48.9	49.6	50.1	50.3	50.5	50.6
	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	276.1	275.2	274.1	272.3	271.3	270.5	269.7	269.4	269.2	269.1
	DLONGITUDE	3.9	3.9	4.0	4.1	4.2	4.3	4.3	4.3	4.4	4.4
	ALBEDO	13.1	14.7	16.6	15.7	15.6	14.5	13.9	14.7	12.4	12.5
	DALBEDO	1.0	1.1	1.2	1.3	1.3	1.3	1.2	1.4	1.2	1.5
NUMBER 36	LATITUDE	24.9	25.6	26.5	27.7	28.3	28.9	29.3	29.5	29.7	29.7
	DLATITUDE	3.1	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
	LONGITUDE	304.1	303.7	303.1	302.3	301.1	301.5	301.2	301.1	300.9	300.9
	DLONGITUDE	3.2	3.2	3.2	3.3	3.3	3.3	3.3	3.3	3.3	3.3
	ALBEDO	18.5	22.9	27.0	28.5	30.5	30.2	31.2	33.0	28.5	30.2
	DALBEDO	.7	.8	.9	1.0	1.1	1.1	1.2	1.2	1.0	1.5
NUMBER 37	LATITUDE	32.0	32.7	33.6	35.0	35.6	36.2	36.7	36.9	37.1	37.2
	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	296.3	295.8	295.2	294.3	293.8	293.4	293.0	292.9	292.7	292.7
	DLONGITUDE	3.3	3.3	3.3	3.4	3.4	3.4	3.4	3.4	3.4	3.5
	ALBEDO	19.1	23.4	28.1	30.1	31.7	32.0	32.9	35.0	30.2	30.8
	DALBEDO	.7	.8	1.0	1.1	1.3	1.4	1.4	1.4	1.4	1.7
NUMBER 38	LATITUDE	12.9	13.6	14.5	15.8	16.4	17.0	17.5	17.6	17.8	17.9
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	328.0	327.6	327.1	326.5	326.1	325.9	325.6	325.5	325.4	325.4
	DLONGITUDE	3.6	3.6	3.6	3.5	3.5	3.5	3.5	3.5	3.5	3.5
	ALBEDO	20.0	25.1	30.0	32.3	34.7	34.7	36.1	38.4	33.5	34.4
	DALBEDO	1.1	1.3	1.4	1.5	1.6	1.7	1.7	1.8	1.6	1.7
NUMBER 39	LATITUDE	6.0	6.7	7.5	8.8	9.4	9.9	10.4	10.6	10.7	10.8
	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	291.0	290.6	290.1	289.3	289.0	288.6	288.4	288.3	288.2	288.1
	DLONGITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	ALBEDO	10.4	12.2	13.7	12.4	12.2	12.2	13.1	14.0	11.4	11.5
	DALBEDO	.6	.4	.3	.4	.4	.5	.4	.5	.2	.4
NUMBER 40	LATITUDE	3.9	4.7	5.7	7.2	7.9	8.6	9.1	9.3	9.5	9.6
	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	335.0	334.7	334.4	333.9	333.8	333.4	333.3	333.2	333.1	333.1
	DLONGITUDE	3.4	3.4	3.4	3.4	3.4	3.3	3.3	3.3	3.3	3.3
	ALBEDO	18.7	23.9	29.4	32.1	34.5	34.9	36.4	38.5	33.6	35.0
	DALBEDO	.8	1.0	1.1	1.2	1.2	1.3	1.3	1.4	1.2	1.5
NUMBER 41	LATITUDE	15.9	16.8	17.8	19.4	20.1	20.8	21.4	21.6	21.8	21.9
	DLATITUDE	3.0	3.0	3.0	3.1	3.1	3.1	3.1	3.1	3.1	3.1
	LONGITUDE	300.9	300.6	300.2	299.7	299.4	299.1	298.9	298.8	298.8	298.7
	DLONGITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	ALBEDO	17.9	24.1	29.5	33.1	35.0	35.3	36.9	38.8	32.5	34.2
	DALBEDO	.5	.5	.7	.8	.7	.7	.8	.8	.7	1.1
NUMBER 42	LATITUDE	21.1	22.1	23.4	25.3	26.3	27.1	27.8	28.1	28.3	28.5
	DLATITUDE	3.1	3.1	3.1	3.1	3.2	3.2	3.2	3.2	3.2	3.2
	LONGITUDE	337.0	336.9	336.9	336.9	336.9	336.9	336.9	336.9	336.9	336.9
	DLONGITUDE	3.2	3.2	3.3	3.3	3.3	3.3	3.3	3.3	3.4	3.4
	ALBEDO	18.5	23.7	28.6	31.3	34.7	35.8	38.7	45.3	36.1	37.5
	DALBEDO	.7	.7	1.0	1.0	1.1	1.2	1.3	1.7	1.4	1.6

Table A-1. Martian albedo (continued)

		WAVELENGTH									
		.60	.64	.70	.89	1.04	1.24	1.61	1.74	2.14	2.27
NUMBER 43	LATITUDE	35.0	36.1	37.6	39.8	40.9	41.9	42.7	43.0	43.3	43.4
	DLATITUDE	3.4	3.4	3.5	3.5	3.6	3.6	3.7	3.7	3.7	3.7
	LONGITUDE	337.1	337.2	337.3	337.6	337.7	337.8	337.9	338.0	338.0	338.1
	DLONGITUDE	3.5	3.6	3.6	3.7	3.7	3.8	3.8	3.8	3.9	3.9
	ALBEDO	17.3	21.4	26.2	26.7	28.9	29.2	30.8	35.6	28.0	29.4
	DALBEDO	.9	1.2	1.6	2.1	2.2	2.3	2.4	2.9	2.4	2.3
NUMBER 44	LATITUDE	14.0	14.9	16.0	17.6	18.3	19.0	19.6	19.8	20.0	20.1
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.1	3.1	3.1
	LONGITUDE	221.0	220.7	220.5	220.0	219.8	219.6	219.4	219.3	219.3	219.3
	DLONGITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.1	3.1	3.1	3.1
	ALBEDO	18.8	24.0	29.5	32.4	35.0	35.6	37.6	40.4	34.9	0.0
	DALBEDO	.6	.5	.6	.6	.8	.8	1.0	1.1	1.2	0.0
NUMBER 46	LATITUDE	11.9	12.8	14.0	15.6	16.4	17.1	17.7	17.9	18.1	18.2
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	202.0	201.7	201.3	200.7	200.4	200.1	199.9	199.8	199.7	199.7
	DLONGITUDE	3.2	3.2	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
	ALBEDO	19.0	23.6	28.6	30.2	32.0	31.9	33.1	35.8	30.0	0.0
	DALBEDO	.6	.8	1.0	1.0	1.1	1.1	1.2	1.3	1.4	0.0
NUMBER 47	LATITUDE	-23.0	-21.9	-20.6	-18.7	-17.7	-16.9	-16.2	-16.0	-15.8	-15.7
	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	224.1	223.9	223.7	223.3	223.1	223.0	222.9	222.8	222.8	222.8
	DLONGITUDE	3.5	3.5	3.5	3.4	3.4	3.3	3.3	3.3	3.3	3.3
	ALBEDO	12.4	14.5	16.9	16.0	16.5	16.7	17.3	18.8	15.3	0.0
	DALBEDO	.7	.8	.8	.7	.8	.8	.9	.9	.9	0.0
NUMBER 49	LATITUDE	13.9	14.9	16.2	17.9	18.8	19.6	20.3	20.5	20.7	20.9
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.1	3.1	3.1	3.1
	LONGITUDE	241.0	240.9	240.8	240.6	240.5	240.4	240.4	240.4	240.3	240.3
	DLONGITUDE	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
	ALBEDO	17.1	21.1	24.8	26.2	27.8	28.0	28.7	31.3	25.4	0.0
	DALBEDO	.5	.7	1.0	1.0	1.2	1.2	1.5	1.7	1.9	0.0
NUMBER 51	LATITUDE	4.1	4.5	5.0	5.7	6.0	6.3	6.6	6.7	6.7	6.8
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	136.0	134.9	133.7	131.8	130.8	130.0	129.3	129.0	128.6	128.6
	DLONGITUDE	3.4	3.4	3.5	3.6	3.6	3.6	3.7	3.7	3.7	3.7
	ALBEDO	19.1	24.0	28.2	31.1	32.6	32.9	34.5	36.5	31.7	33.5
	DALBEDO	.8	1.0	1.3	1.5	1.7	1.8	2.0	2.2	2.0	2.3
NUMBER 52	LATITUDE	17.8	18.2	18.7	19.3	19.7	19.9	20.2	20.3	20.3	20.4
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.1	3.1	3.1	3.1	3.1
	LONGITUDE	131.0	129.8	128.3	126.1	125.0	124.0	123.1	122.8	122.5	122.4
	DLONGITUDE	3.6	3.7	3.8	3.9	4.0	4.0	4.1	4.1	4.1	4.1
	ALBEDO	19.5	24.2	29.2	31.6	33.3	33.3	34.9	36.6	31.3	33.4
	DALBEDO	1.0	1.5	1.8	2.2	2.5	2.6	2.9	3.2	2.8	3.3
NUMBER 53	LATITUDE	-13.9	-13.5	-13.0	-12.2	-11.8	-11.5	-11.2	-11.1	-11.0	-11.0
	DLATITUDE	3.3	3.3	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
	LONGITUDE	137.0	136.0	134.9	133.2	132.4	131.6	131.0	130.8	130.6	130.5
	DLONGITUDE	3.7	3.8	3.8	3.8	3.9	3.9	3.9	3.9	3.9	3.9
	ALBEDO	19.1	23.5	28.5	30.7	32.6	33.1	34.8	37.0	32.0	34.1
	DALBEDO	1.2	1.6	1.9	2.1	2.4	2.5	2.9	3.2	2.6	3.0
NUMBER 55	LATITUDE	-45.0	-44.2	-43.2	-41.9	-41.3	-40.7	-40.2	-40.1	-39.9	-39.9
	DLATITUDE	5.2	5.1	5.0	4.8	4.7	4.7	4.6	4.6	4.6	4.6
	LONGITUDE	153.8	152.9	151.8	150.1	149.3	148.6	148.0	147.8	147.6	147.5
	DLONGITUDE	5.3	5.2	5.2	5.1	5.0	5.0	4.9	4.9	4.9	4.9
	ALBEDO	13.3	15.0	17.1	17.0	17.5	17.5	18.5	19.9	15.5	15.8
	DALBEDO	2.4	2.6	2.9	2.7	2.8	2.7	2.8	3.2	2.6	2.6

Table A-1. Martian albedo (continued)

		WAVELENGTH									
		.60	.64	.70	.89	1.04	1.24	1.61	1.74	2.14	2.27
NUMBER 56	LATITUDE	9.9	10.4	11.0	11.8	12.2	12.6	12.9	13.0	13.1	13.2
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	158.0	157.2	156.2	154.8	154.0	153.4	152.8	152.6	152.4	152.3
	DLONGITUDE	3.1	3.1	3.1	3.1	3.1	3.1	3.2	3.2	3.2	3.2
	ALBEDO	18.0	23.2	28.5	31.4	33.5	34.1	35.8	39.4	33.4	34.3
	DALBEDO	.4	.5	.6	.7	.7	.8	.9	1.0	1.1	1.4
NUMBER 57	LATITUDE	25.9	26.4	27.0	27.9	28.4	28.7	29.1	29.2	29.3	29.3
	DLATITUDE	3.1	3.1	3.1	3.2	3.2	3.2	3.2	3.2	3.2	3.2
	LONGITUDE	157.9	157.0	155.9	154.2	153.3	152.6	151.9	151.7	151.5	151.4
	DLONGITUDE	3.2	3.2	3.3	3.3	3.3	3.4	3.4	3.4	3.4	3.4
	ALBEDO	19.2	23.9	28.9	31.6	33.7	33.9	35.7	38.3	33.9	34.0
	DALBEDO	.8	.9	1.1	1.2	1.3	1.4	1.5	1.7	1.6	1.8
NUMBER 61	LATITUDE	-4.0	-3.5	-2.8	-1.9	-1.4	-1.0	-.7	-.6	-.5	-.4
	DLATITUDE	3.1	3.1	3.1	3.1	3.1	3.1	3.0	3.0	3.0	3.0
	LONGITUDE	165.0	164.3	163.5	162.2	161.6	161.1	160.6	160.5	160.3	160.2
	DLONGITUDE	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.2	3.2
	ALBEDO	17.5	23.1	27.4	29.9	32.2	32.6	34.3	37.6	31.2	32.4
	DALBEDO	.5	.6	.8	.7	.7	.7	.8	.9	.9	1.1
NUMBER 63	LATITUDE	-34.9	-34.2	-33.3	-32.1	-31.5	-30.9	-30.5	-30.3	-30.2	-30.1
	DLATITUDE	4.2	4.2	4.1	4.0	4.0	3.9	3.9	3.9	3.9	3.9
	LONGITUDE	165.7	165.0	164.2	163.0	162.4	161.8	161.4	161.3	161.1	161.0
	DLONGITUDE	4.3	4.2	4.2	4.1	4.1	4.1	4.1	4.1	4.1	4.1
	ALBEDO	12.4	15.1	16.4	15.3	16.3	16.2	17.1	17.9	15.0	15.4
	DALBEDO	1.3	1.5	1.6	1.5	1.5	1.5	1.5	1.6	1.5	1.5
NUMBER 65	LATITUDE	9.9	10.5	11.1	12.0	12.4	12.8	13.2	13.3	13.4	13.5
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	158.0	157.3	156.4	155.1	154.5	153.9	153.4	153.2	153.0	152.9
	DLONGITUDE	3.2	3.2	3.2	3.3	3.3	3.3	3.3	3.3	3.3	3.3
	ALBEDO	18.0	23.8	28.4	30.6	32.8	32.9	34.3	37.9	31.1	33.6
	DALBEDO	.5	.7	.9	1.0	1.1	1.3	1.4	1.6	1.8	1.8
NUMBER 66	LATITUDE	19.0	19.6	20.3	21.3	21.8	22.3	22.6	22.8	22.9	23.0
	DLATITUDE	3.0	3.0	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
	LONGITUDE	178.0	177.4	176.6	175.5	174.9	174.4	173.9	173.8	173.6	173.5
	DLONGITUDE	3.0	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
	ALBEDO	17.8	23.8	28.7	31.5	33.9	34.3	36.1	38.9	32.2	32.9
	DALBEDO	.6	.7	.6	.7	.7	.8	.8	1.0	1.1	1.1
NUMBER 67	LATITUDE	31.9	32.5	33.2	34.3	34.9	35.3	35.7	35.9	36.0	36.1
	DLATITUDE	3.2	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.4	3.4
	LONGITUDE	170.7	170.0	169.0	167.6	166.9	166.2	165.6	165.5	165.3	165.2
	DLONGITUDE	3.3	3.3	3.4	3.4	3.4	3.5	3.5	3.5	3.5	3.5
	ALBEDO	18.5	24.1	28.8	31.9	34.4	34.9	36.8	39.9	34.3	34.2
	DALBEDO	.8	1.0	1.3	1.5	1.7	1.7	1.9	2.1	2.1	2.2
NUMBER 70	LATITUDE	8.0	8.6	9.3	10.4	10.9	11.3	11.7	11.9	12.0	12.0
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	182.0	181.4	180.8	179.8	179.3	178.8	178.4	178.3	178.2	178.1
	DLONGITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	ALBEDO	17.4	22.8	27.6	29.7	32.3	32.8	34.1	37.7	32.2	31.7
	DALBEDO	.3	.2	.5	.4	.3	.3	.3	.6	.6	.9
NUMBER 71	LATITUDE	-8.0	-7.4	-6.6	-5.5	-5.0	-4.5	-4.1	-3.9	-3.8	-3.7
	DLATITUDE	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
	LONGITUDE	184.0	183.5	182.8	181.9	181.4	181.0	180.6	180.5	180.4	180.3
	DLONGITUDE	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
	ALBEDO	15.8	20.5	24.6	26.9	29.2	29.7	31.5	34.4	29.2	28.7
	DALBEDO	.7	.6	.7	.6	.7	.6	.7	.8	1.0	1.2

Table A-1. Martian albedo (continued)

		WAVELENGTH									
		.60	.64	.70	.69	1.04	1.24	1.61	1.74	2.14	2.27
NUMBER 72	LATITUDE	-26.0	-25.3	-24.4	-23.1	-22.5	-21.9	-21.4	-21.3	-21.1	-21.1
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	181.0	180.5	179.8	178.9	178.4	178.0	177.7	177.6	177.4	177.4
	DLONGITUDE	3.7	3.7	3.6	3.6	3.6	3.6	3.5	3.5	3.5	3.5
	ALBEDO	12.2	14.6	16.4	16.0	17.4	17.8	19.0	20.5	16.0	16.7
	DALBEDO	.9	1.1	1.0	1.0	1.1	1.1	1.2	1.3	1.2	1.5
NUMBER 73	LATITUDE	-34.9	-34.1	-33.0	-31.5	-30.6	-30.1	-29.6	-29.4	-29.2	-29.2
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	193.2	197.5	196.6	195.4	194.8	194.3	193.9	193.7	193.6	193.5
	DLONGITUDE	4.3	4.2	4.1	4.0	4.0	3.9	3.9	3.9	3.9	3.9
	ALBEDO	11.8	13.4	14.7	14.1	14.7	14.7	15.7	17.0	13.2	14.6
	DALBEDO	1.3	1.3	1.4	1.2	1.2	1.2	1.2	1.4	1.1	1.2
NUMBER 74	LATITUDE	-25.8	-25.1	-24.2	-22.9	-22.3	-21.8	-21.3	-21.2	-21.0	-20.9
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	166.7	166.2	165.7	164.9	164.5	164.1	163.8	163.7	163.6	163.5
	DLONGITUDE	3.9	3.9	3.9	3.9	3.9	3.8	3.8	3.8	3.8	3.8
	ALBEDO	12.4	14.0	15.5	15.1	15.9	16.3	17.2	18.9	14.7	15.0
	DALBEDO	1.0	1.1	1.2	1.2	1.3	1.4	1.4	1.6	1.5	1.5
NUMBER 75	LATITUDE	23.1	23.7	24.4	25.4	25.9	26.4	26.8	26.9	27.0	27.1
	DLATITUDE	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
	LONGITUDE	155.0	154.2	153.2	151.7	150.9	150.2	149.5	149.3	149.1	149.0
	DLONGITUDE	3.7	3.6	3.8	3.9	4.0	4.0	4.1	4.1	4.1	4.1
	ALBEDO	19.7	25.2	29.9	33.0	35.9	36.3	38.4	42.2	34.9	36.0
	DALBEDO	1.3	1.6	2.1	2.4	2.7	2.9	3.1	3.6	3.1	3.6
NUMBER 76	LATITUDE	15.0	15.6	16.4	17.6	18.2	18.7	19.1	19.3	19.4	19.5
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	190.0	189.5	188.9	188.0	187.6	187.2	186.9	186.8	186.7	186.6
	DLONGITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	ALBEDO	18.3	23.5	27.9	29.6	32.5	32.5	34.1	37.9	31.4	33.1
	DALBEDO	.5	.4	.4	.5	.5	.6	.6	.7	1.3	1.3
NUMBER 77	LATITUDE	5.0	5.7	6.5	7.7	8.2	8.8	9.2	9.3	9.5	9.6
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	195.0	194.6	194.0	193.2	192.8	192.5	192.2	192.1	192.0	191.9
	DLONGITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	ALBEDO	18.2	22.5	27.3	29.1	31.5	31.9	33.6	37.0	30.0	31.4
	DALBEDO	.5	.5	.5	.4	.4	.4	.4	.5	.5	1.4
NUMBER 78	LATITUDE	5.0	5.7	6.5	7.7	8.3	8.9	9.3	9.5	9.6	9.7
	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	204.0	203.6	203.1	202.3	201.9	201.6	201.3	201.2	201.1	201.1
	DLONGITUDE	3.1	3.1	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	ALBEDO	17.4	22.3	26.4	27.7	29.8	30.0	31.2	34.1	27.3	28.5
	DALBEDO	.5	.6	.5	.5	.6	.5	.7	.6	.9	1.4
NUMBER 79	LATITUDE	-1.8	-1.1	.8	2.0	2.7	3.2	3.7	3.8	4.0	4.1
	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	215.1	214.6	214.1	213.3	212.9	212.6	212.3	212.2	212.1	212.1
	DLONGITUDE	3.3	3.3	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
	ALBEDO	15.5	20.5	24.3	25.4	27.5	27.6	28.5	31.3	25.5	27.0
	DALBEDO	.9	1.0	.9	.9	1.0	.9	1.0	1.0	1.0	1.3
NUMBER 80	LATITUDE	-17.0	-16.2	-15.3	-14.0	-13.3	-12.8	-12.3	-12.1	-11.9	-11.9
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	196.9	196.4	195.9	195.1	194.8	194.4	194.2	194.1	194.0	193.9
	DLONGITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	ALBEDO	11.7	14.7	17.2	17.3	18.6	19.4	21.0	22.7	18.5	20.3
	DALBEDO	.7	.8	.8	.9	1.3	1.6	1.7	2.1	1.7	2.2

Table A-1. Martian albedo (continued)

		WAVELENGTH									
		.60	.64	.70	.89	1.04	1.24	1.61	1.74	2.14	2.27
NUMBER 81	LATITUDE	-21.9	-21.0	-20.0	-18.6	-17.9	-17.3	-16.6	-16.6	-16.4	-16.3
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	208.4	207.3	207.2	206.4	205.9	205.6	205.3	205.1	205.0	205.0
	DLONGITUDE	3.6	3.6	3.5	3.5	3.4	3.4	3.4	3.4	3.4	3.4
	ALBEDO	11.1	13.0	14.5	13.7	14.4	14.7	15.5	16.8	14.3	14.3
	DALBEDO	.8	.8	.9	.8	.7	.8	.9	.9	.8	.8
NUMBER 82	LATITUDE	29.9	30.6	31.5	32.9	33.5	34.1	34.6	34.8	34.9	35.0
	DLATITUDE	3.2	3.2	3.2	3.3	3.3	3.3	3.3	3.3	3.3	3.3
	LONGITUDE	185.8	185.3	184.6	183.5	183.0	182.5	182.1	182.0	181.8	181.8
	DLONGITUDE	3.3	3.3	3.3	3.4	3.4	3.4	3.4	3.4	3.4	3.4
	ALBEDO	19.1	24.5	29.7	31.9	34.5	35.1	37.0	40.0	33.0	35.2
	DALBEDO	1.0	1.0	1.2	1.5	1.6	1.7	1.8	2.1	1.7	1.9
NUMBER 85	LATITUDE	44.9	45.8	46.9	48.5	49.3	50.0	50.6	50.8	51.0	51.1
	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	185.7	185.0	184.0	182.5	181.7	181.0	180.3	180.1	179.9	179.8
	DLONGITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	ALBEDO	16.5	21.1	25.4	25.9	27.9	28.1	29.7	32.6	27.4	27.2
	DALBEDO	1.0	1.3	1.5	1.8	2.0	2.1	2.4	2.7	2.3	2.6
NUMBER 86	LATITUDE	20.0	20.8	21.7	23.1	23.8	24.4	24.9	25.0	25.2	25.3
	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	196.0	195.6	195.2	194.4	194.1	193.7	193.4	193.4	193.3	193.2
	DLONGITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	ALBEDO	15.6	20.4	24.1	25.7	28.1	28.7	30.6	33.3	27.9	28.6
	DALBEDO	.6	.8	.9	1.2	1.4	1.3	1.3	1.5	1.2	1.3
NUMBER 87	LATITUDE	42.0	42.9	44.1	45.8	46.6	47.4	48.0	48.3	48.5	48.6
	DLATITUDE	3.6	3.6	3.6	3.7	3.8	3.8	3.8	3.8	3.9	3.9
	LONGITUDE	204.2	203.8	203.2	202.4	202.0	201.6	201.3	201.2	201.0	201.0
	DLONGITUDE	3.6	3.6	3.6	3.7	3.8	3.8	3.8	3.9	3.9	3.9
	ALBEDO	18.3	23.5	27.7	28.9	30.7	31.0	32.5	35.5	29.0	30.2
	DALBEDO	1.2	1.5	1.9	2.2	2.5	2.7	2.9	3.3	2.7	3.6
NUMBER 89	LATITUDE	26.0	26.8	27.8	29.3	30.1	30.8	31.3	31.5	31.7	31.8
	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	210.1	209.7	209.4	208.8	208.5	208.3	208.1	208.0	207.9	207.9
	DLONGITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	ALBEDO	19.1	24.0	29.3	31.3	33.5	33.7	35.1	37.5	31.8	33.4
	DALBEDO	.5	.6	.7	.8	.9	1.0	1.0	1.0	1.4	1.5
NUMBER 90	LATITUDE	22.8	23.6	24.6	26.1	26.8	27.4	28.0	28.2	28.3	28.4
	DLATITUDE	3.1	3.1	3.1	3.1	3.1	3.2	3.2	3.2	3.2	3.2
	LONGITUDE	184.9	184.4	183.8	182.9	182.4	182.0	181.6	181.5	181.4	181.3
	DLONGITUDE	3.3	3.3	3.4	3.4	3.4	3.5	3.5	3.5	3.5	3.5
	ALBEDO	19.4	24.1	29.1	32.1	34.9	35.0	36.4	39.3	34.2	36.2
	DALBEDO	.8	.9	1.2	1.4	1.5	1.6	1.7	2.0	1.9	2.0
NUMBER 91	LATITUDE	19.9	20.8	21.8	23.3	24.0	24.7	25.3	25.4	25.6	25.7
	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	212.1	211.8	211.5	211.0	210.7	210.5	210.3	210.3	210.2	210.2
	DLONGITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	ALBEDO	19.1	23.4	28.7	30.9	33.5	33.6	34.8	36.8	31.9	34.2
	DALBEDO	.7	.5	.5	.6	.7	.8	.9	.9	.8	1.0
NUMBER 92	LATITUDE	32.0	32.9	34.0	35.6	36.4	37.2	37.8	38.0	38.2	38.3
	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	208.3	208.0	207.6	207.0	206.7	206.4	206.1	206.1	206.0	205.9
	DLONGITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	ALBEDO	18.9	24.3	29.2	31.3	33.6	33.6	35.1	37.2	32.1	33.9
	DALBEDO	.6	.9	1.0	1.1	1.2	1.3	1.3	1.5	1.6	1.6

Table A-1. Martian albedo (continued)

		WAVELENGTH									
		.60	.64	.70	.89	1.04	1.24	1.61	1.74	2.14	2.27
NUMBER	LATITUDE	25.0	25.9	26.9	28.5	29.3	30.0	30.6	30.8	31.0	31.1
93	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	203.0	202.7	202.2	201.6	201.3	201.0	200.7	200.7	200.6	200.5
	DLONGITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	ALBEDO	18.7	23.6	28.5	31.2	33.9	34.0	35.3	37.5	32.6	33.8
	DALBEDO	.5	.7	.6	.8	.9	.9	.9	1.0	1.2	1.3
NUMBER	LATITUDE	27.0	27.9	29.0	30.6	31.4	32.1	32.7	32.9	33.1	33.2
94	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	217.1	216.8	216.5	216.1	215.9	215.7	215.6	215.5	215.4	215.4
	DLONGITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	ALBEDO	19.6	24.8	29.9	32.0	34.0	33.8	35.0	37.0	31.4	32.6
	DALBEDO	.6	.8	.8	1.0	1.0	1.1	1.2	1.3	1.1	1.6
NUMBER	LATITUDE	-19.9	-18.9	-17.7	-16.0	-15.2	-14.4	-13.8	-13.6	-13.4	-13.3
95	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	219.3	218.9	218.6	218.0	217.7	217.5	217.3	217.3	217.2	217.2
	DLONGITUDE	3.5	3.5	3.4	3.4	3.3	3.3	3.3	3.3	3.3	3.3
	ALBEDO	11.4	12.8	14.3	13.2	13.5	13.4	14.0	14.6	11.6	12.9
	DALBEDO	.6	.6	.8	.6	.6	.6	.7	.7	.7	.9
NUMBER	LATITUDE	6.1	7.0	8.2	9.8	10.6	11.3	11.9	12.1	12.3	12.4
96	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	225.0	224.8	224.6	224.2	224.1	223.9	223.8	223.7	223.7	223.7
	DLONGITUDE	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
	ALBEDO	16.7	20.2	23.8	25.3	27.0	26.8	27.5	29.3	25.1	25.5
	DALBEDO	.6	.7	.8	1.0	1.0	1.0	1.2	1.2	1.1	.9
NUMBER	LATITUDE	14.9	15.8	17.0	18.6	19.5	20.2	20.8	21.0	21.3	21.4
97	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.1	3.1	3.1	3.1	3.1
	LONGITUDE	231.0	230.9	230.7	230.5	230.4	230.3	230.2	230.1	230.1	230.1
	DLONGITUDE	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
	ALBEDO	14.9	17.1	19.2	18.8	19.1	18.1	17.5	18.5	15.1	14.9
	DALBEDO	.7	.7	.7	.8	.7	.7	.8	.8	1.0	1.3
NUMBER	LATITUDE	33.1	34.1	35.4	37.2	38.2	39.0	39.7	40.0	40.2	40.3
98	DLATITUDE	3.3	3.3	3.3	3.4	3.4	3.4	3.5	3.5	3.5	3.5
	LONGITUDE	231.9	231.9	231.8	231.8	231.8	231.8	231.8	231.8	231.8	231.8
	DLONGITUDE	3.4	3.5	3.5	3.6	3.6	3.6	3.6	3.6	3.7	3.7
	ALBEDO	15.5	17.6	20.5	19.2	19.6	18.5	17.5	18.6	14.5	14.0
	DALBEDO	.9	1.2	1.2	1.3	1.3	1.3	1.3	1.4	1.4	1.9
NUMBER	LATITUDE	49.9	51.2	52.7	55.1	56.3	57.4	58.4	58.7	59.0	59.2
99	DLATITUDE	3.9	4.0	4.1	4.3	4.4	4.5	4.6	4.6	4.6	4.6
	LONGITUDE	227.4	227.4	227.5	227.6	227.7	227.8	227.9	227.9	227.9	228.0
	DLONGITUDE	4.0	4.1	4.2	4.4	4.5	4.6	4.7	4.7	4.7	4.8
	ALBEDO	15.9	18.3	20.5	19.8	20.1	19.3	18.8	19.8	17.2	17.1
	DALBEDO	1.4	1.8	2.3	2.4	2.6	2.7	2.8	3.1	2.9	3.3
NUMBER	LATITUDE	26.0	27.0	28.2	30.0	31.0	31.8	32.5	32.7	32.9	33.0
100	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	210.0	209.7	209.4	208.9	208.7	208.4	208.2	208.2	208.1	208.1
	DLONGITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	ALBEDO	19.1	24.0	29.4	32.3	34.4	34.6	35.7	37.9	32.9	33.0
	DALBEDO	.6	.5	.8	.8	1.0	1.0	1.1	1.3	1.6	1.5
NUMBER	LATITUDE	9.0	10.0	11.1	12.8	13.7	14.5	15.1	15.3	15.5	15.6
101	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	191.0	190.7	190.4	189.9	189.6	189.3	189.1	189.0	189.0	188.9
	DLONGITUDE	3.3	3.3	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
	ALBEDO	18.3	21.7	27.6	30.2	31.9	32.5	33.7	36.2	31.0	32.3
	DALBEDO	.7	.9	1.0	1.2	1.3	1.3	1.4	1.5	1.7	2.0

Table A-1. Martian albedo (continued)

		WAVELENGTH									
		.60	.64	.70	.89	1.04	1.24	1.61	1.74	2.14	2.27
NUMBER 102	LATITUDE	-18.0	-16.9	-15.5	-13.6	-12.6	-11.8	-11.1	-10.9	-10.6	-10.5
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	227.0	226.7	226.5	226.1	225.9	225.7	225.6	225.6	225.5	225.5
	DLONGITUDE	3.4	3.4	3.3	3.3	3.3	3.3	3.2	3.2	3.2	3.2
	ALBEDO	11.2	12.0	14.3	13.7	13.2	13.3	13.6	14.6	11.2	11.5
	DALBEDO	.6	.6	.6	.5	.5	.5	.5	.5	.7	1.1
NUMBER 111	LATITUDE	14.9	15.5	16.2	17.2	17.7	18.2	18.6	18.7	18.8	18.9
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	110.0	109.2	108.2	106.8	106.1	105.5	105.0	104.8	104.6	104.5
	DLONGITUDE	3.5	3.4	3.4	3.4	3.4	3.3	3.3	3.3	3.3	3.3
	ALBEDO	16.5	21.4	25.9	29.1	31.4	32.0	33.7	34.8	31.1	31.8
	DALBEDO	1.2	1.5	1.8	1.9	2.1	2.1	2.2	2.3	2.1	2.3
NUMBER 112	LATITUDE	12.0	12.5	13.2	14.1	14.5	14.9	15.3	15.4	15.5	15.6
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	83.0	82.3	81.4	80.1	79.4	78.8	78.3	78.1	78.0	77.9
	DLONGITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	ALBEDO	16.2	21.2	25.4	27.7	29.7	29.9	31.4	32.1	28.1	30.3
	DALBEDO	.4	.4	.6	.6	.8	.7	.8	1.0	1.7	1.1
NUMBER 120	LATITUDE	11.1	11.7	12.5	13.6	14.1	14.6	15.0	15.2	15.3	15.4
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	118.0	117.4	116.6	115.5	115.0	114.5	114.1	114.0	113.8	113.8
	DLONGITUDE	3.4	3.4	3.4	3.3	3.3	3.3	3.3	3.3	3.3	3.3
	ALBEDO	17.8	23.7	28.4	31.2	33.5	34.2	35.8	37.7	31.9	33.4
	DALBEDO	1.1	1.4	1.7	1.8	1.9	2.0	2.0	2.2	2.1	2.4
NUMBER 121	LATITUDE	12.0	12.6	13.3	14.3	14.8	15.3	15.7	15.8	15.9	16.0
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	91.0	90.4	89.7	88.6	88.0	87.6	87.1	87.0	86.9	86.8
	DLONGITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	ALBEDO	17.3	23.2	28.1	31.0	33.0	33.6	34.6	36.6	31.4	33.3
	DALBEDO	.5	.4	.5	.5	.6	.6	.7	.7	.8	1.4
NUMBER 122	LATITUDE	12.0	12.6	13.3	14.3	14.8	15.2	15.6	15.7	15.8	15.9
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	83.0	82.4	81.6	80.5	79.9	79.4	79.0	78.9	78.7	78.7
	DLONGITUDE	3.0	3.0	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
	ALBEDO	16.2	21.0	25.9	28.6	30.9	31.4	32.9	34.8	29.5	31.8
	DALBEDO	.3	.5	.5	.6	.6	.7	.8	.9	1.0	1.1
NUMBER 125	LATITUDE	39.0	39.7	40.6	41.8	42.4	43.0	43.5	43.6	43.8	43.9
	DLATITUDE	3.4	3.4	3.5	3.5	3.5	3.5	3.6	3.6	3.6	3.6
	LONGITUDE	92.1	91.4	90.5	89.2	88.5	87.8	87.3	87.1	86.9	86.8
	DLONGITUDE	3.4	3.4	3.5	3.5	3.5	3.6	3.6	3.6	3.6	3.6
	ALBEDO	17.8	23.8	28.3	30.7	32.6	33.0	34.1	36.7	30.7	31.6
	DALBEDO	1.1	1.4	1.7	2.1	2.3	2.5	2.7	3.0	2.6	2.8
NUMBER 126	LATITUDE	28.0	28.6	29.4	30.6	31.2	31.7	32.1	32.3	32.4	32.5
	DLATITUDE	3.1	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
	LONGITUDE	93.9	93.3	92.5	91.4	90.9	90.3	89.9	89.8	89.6	89.5
	DLONGITUDE	3.1	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.3	3.3
	ALBEDO	17.7	23.1	28.2	31.0	33.6	34.1	35.5	38.7	32.4	35.4
	DALBEDO	.8	.9	1.1	1.2	1.4	1.5	1.6	1.9	1.7	1.8
NUMBER 127	LATITUDE	15.0	15.6	16.4	17.5	18.1	18.6	19.0	19.1	19.3	19.3
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	96.0	95.4	94.8	93.8	93.4	92.9	92.6	92.4	92.3	92.3
	DLONGITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	ALBEDO	18.5	23.5	29.0	31.6	34.2	34.9	36.1	39.0	33.8	34.1
	DALBEDO	.5	.4	.6	.6	.7	.7	.8	.9	.9	1.2

Table A-1. Martian albedo (continued)

		WAVELENGTH									
		.60	.64	.70	.89	1.04	1.24	1.61	1.74	2.14	2.27
NUMBER	LATITUDE	3.0	3.7	4.5	5.6	6.2	6.7	7.1	7.3	7.4	7.5
128	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	96.9	96.5	95.9	95.0	94.6	94.2	93.9	93.8	93.6	93.6
	DLONGITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	ALBEDO	18.0	23.4	29.2	31.5	33.8	34.3	35.4	37.8	31.7	34.4
	DALBEDO	.5	.4	.4	.6	.5	.5	.6	.6	.6	.6
NUMBER	LATITUDE	-10.0	-9.3	-8.4	-7.2	-6.6	-6.1	-5.6	-5.5	-5.3	-5.3
129	DLATITUDE	3.2	3.2	3.2	3.2	3.1	3.1	3.1	3.1	3.1	3.1
	LONGITUDE	96.9	96.4	95.8	95.0	94.6	94.2	93.9	93.8	93.7	93.6
	DLONGITUDE	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.1	3.1	3.1
	ALBEDO	17.6	23.1	27.9	30.6	33.1	33.4	34.8	37.2	31.7	31.8
	DALBEDO	.6	.7	.8	.8	.9	.9	.9	1.0	1.1	1.3
NUMBER	LATITUDE	-21.0	-20.2	-19.3	-18.0	-17.3	-16.7	-16.2	-16.1	-15.9	-15.8
130	DLATITUDE	3.5	3.5	3.5	3.4	3.4	3.4	3.4	3.4	3.4	3.4
	LONGITUDE	96.1	95.6	95.0	94.2	93.8	93.5	93.2	93.1	93.0	92.9
	DLONGITUDE	3.5	3.5	3.5	3.5	3.4	3.4	3.4	.4	3.4	3.4
	ALBEDO	15.8	21.0	25.4	27.1	29.3	29.5	30.8	33.3	28.8	28.0
	DALBEDO	.9	1.1	1.3	1.3	1.4	1.4	1.4	1.6	1.4	1.6
NUMBER	LATITUDE	34.0	34.7	35.6	36.9	37.6	38.2	38.7	38.9	39.0	39.1
132	DLATITUDE	3.3	3.3	3.3	3.3	3.4	3.4	3.4	3.4	3.4	3.4
	LONGITUDE	99.7	99.1	98.4	97.4	96.8	96.3	95.9	95.8	95.6	95.5
	DLONGITUDE	3.3	3.3	3.3	3.4	3.4	3.4	3.4	3.4	3.4	3.4
	ALBEDO	19.5	24.4	29.8	33.5	35.4	36.3	38.1	41.5	34.6	35.4
	DALBEDO	.9	1.2	1.5	1.9	2.0	2.1	2.4	2.7	2.3	2.8
NUMBER	LATITUDE	3.0	3.7	4.6	5.8	6.4	7.0	7.4	7.6	7.7	7.8
133	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	98.0	97.6	97.1	96.3	95.9	95.6	95.3	95.2	95.1	95.1
	DLONGITUDE	3.1	3.1	3.0	3.0	3.0	3.1	3.1	3.1	3.1	3.1
	ALBEDO	18.7	24.2	29.7	32.1	34.4	34.7	36.0	38.7	33.4	33.6
	DALBEDO	.5	.6	.5	.5	.5	.5	.6	.7	.7	.9
NUMBER	LATITUDE	35.9	36.7	37.7	39.2	39.9	40.6	41.1	41.3	41.5	41.6
135	DLATITUDE	3.3	3.3	3.4	3.4	3.4	3.5	3.5	3.5	3.5	3.5
	LONGITUDE	120.3	119.9	119.5	118.8	118.5	118.2	117.9	117.8	117.7	117.7
	DLONGITUDE	3.4	3.4	3.4	3.5	3.5	3.5	3.5	3.5	3.5	3.5
	ALBEDO	19.3	24.6	30.2	32.0	34.6	34.7	36.2	39.3	32.7	34.7
	DALBEDO	1.3	1.6	2.0	2.3	2.5	2.6	2.9	3.1	2.9	3.0
NUMBER	LATITUDE	25.0	25.7	26.7	28.0	28.7	29.3	29.9	30.0	30.2	30.3
136	DLATITUDE	3.1	3.1	3.1	3.1	3.2	3.2	3.2	3.2	3.2	3.2
	LONGITUDE	117.1	116.7	116.2	115.6	115.2	114.9	114.7	114.6	114.5	114.4
	DLONGITUDE	3.1	3.1	3.1	3.2	3.2	3.2	3.2	3.2	3.2	3.2
	ALBEDO	18.7	24.1	29.3	31.6	34.1	34.4	36.1	39.5	31.9	34.1
	DALBEDO	.8	.9	1.2	1.3	1.5	1.5	1.6	1.8	1.8	1.7
NUMBER	LATITUDE	10.1	10.8	11.7	13.1	13.7	14.3	14.8	15.0	15.2	15.2
137	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	119.0	118.6	118.2	117.6	117.2	117.0	116.7	116.6	116.6	116.5
	DLONGITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	ALBEDO	18.8	24.3	29.2	31.6	34.2	34.3	35.8	38.6	31.4	33.6
	DALBEDO	.6	.9	.9	.9	1.0	1.0	1.0	1.2	1.3	1.2
NUMBER	LATITUDE	.0	.8	1.8	3.1	3.8	4.4	4.9	5.1	5.2	5.3
138	DLATITUDE	3.1	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	120.0	119.7	119.2	118.6	118.2	118.0	117.7	117.6	117.6	117.5
	DLONGITUDE	3.1	3.1	3.1	3.1	3.1	3.1	3.0	3.0	3.0	3.0
	ALBEDO	18.8	24.0	28.8	30.9	33.2	33.3	34.8	38.1	32.2	33.9
	DALBEDO	.7	.7	.9	.8	.8	.9	.9	1.0	1.2	1.6

Table A-1. Martian albedo (continued)

		WAVELENGTH									
		.60	.64	.70	.89	1.04	1.24	1.61	1.74	2.14	2.27
NUMBER 139	LATITUDE	-8.0	-7.2	-6.2	-4.8	-4.1	-3.4	-2.9	-2.7	-2.6	-2.5
	DLATITUDE	3.2	3.2	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
	LONGITUDE	120.0	119.6	119.2	118.5	118.2	117.9	117.7	117.6	117.5	117.5
	DLONGITUDE	3.2	3.2	3.2	3.1	3.1	3.1	3.1	3.1	3.1	3.1
	ALBEDO	18.3	22.7	27.9	30.1	32.1	32.5	33.9	36.7	31.1	31.4
	DALBEDO	.8	.8	1.0	.9	1.0	1.0	1.0	1.1	1.1	1.1
NUMBER 140	LATITUDE	-24.0	-23.0	-21.9	-20.2	-19.4	-18.7	-18.1	-17.9	-17.7	-17.6
	DLATITUDE	3.7	3.6	3.6	3.5	3.5	3.5	3.4	3.4	3.4	3.4
	LONGITUDE	121.1	120.7	120.1	119.4	119.0	118.7	118.4	118.3	118.2	118.2
	DLONGITUDE	3.7	3.7	3.6	3.5	3.5	3.5	3.5	3.4	3.4	3.4
	ALBEDO	17.5	22.3	26.9	29.1	31.2	31.6	33.1	36.2	30.0	30.5
	DALBEDO	1.3	1.6	1.8	1.8	1.8	1.9	1.9	2.2	1.8	1.9
NUMBER 141	LATITUDE	10.0	10.8	11.7	13.1	13.8	14.4	14.9	15.1	15.3	15.3
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	111.0	110.6	110.2	109.6	109.3	109.0	108.7	108.7	108.6	108.5
	DLONGITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	ALBEDO	19.1	24.3	30.1	32.5	35.0	35.6	37.0	40.2	34.3	35.7
	DALBEDO	.4	.5	.5	.5	.5	.6	.6	.8	.8	1.3
NUMBER 142	LATITUDE	-10.1	-9.2	-8.2	-6.8	-6.1	-5.5	-4.9	-4.7	-4.6	-4.5
	DLATITUDE	3.2	3.2	3.2	3.1	3.1	3.1	3.1	3.1	3.1	3.1
	LONGITUDE	94.1	93.8	93.4	92.8	92.5	92.3	92.1	92.0	91.9	91.9
	DLONGITUDE	3.4	3.4	3.4	3.3	3.3	3.3	3.3	3.3	3.3	3.3
	ALBEDO	18.0	23.4	27.7	30.3	32.4	33.1	35.3	37.8	32.0	32.8
	DALBEDO	.8	1.1	1.1	1.2	1.3	1.2	1.3	1.5	1.6	1.6
NUMBER 143	LATITUDE	35.9	36.7	37.8	39.3	40.1	40.7	41.3	41.5	41.7	41.8
	DLATITUDE	3.3	3.3	3.4	3.4	3.4	3.5	3.5	3.5	3.5	3.5
	LONGITUDE	89.8	89.1	88.2	86.8	86.1	85.4	84.8	84.6	84.4	84.3
	DLONGITUDE	3.6	3.7	3.7	3.8	3.9	3.9	4.0	4.0	4.0	4.0
	ALBEDO	19.0	25.5	30.7	33.6	35.5	36.4	39.1	42.5	35.0	36.9
	DALBEDO	1.2	1.8	2.2	2.7	2.9	3.1	3.5	4.0	3.4	3.7
NUMBER 144	LATITUDE	12.8	13.5	14.5	15.9	16.6	17.2	17.7	17.9	18.1	18.1
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	91.0	90.6	90.0	89.2	88.8	88.4	88.1	88.0	87.9	87.8
	DLONGITUDE	3.3	3.3	3.3	3.3	3.4	3.4	3.4	3.4	3.4	3.4
	ALBEDO	19.6	24.9	29.9	32.6	35.0	35.5	36.7	39.9	33.5	35.0
	DALBEDO	.8	.9	1.1	1.3	1.5	1.5	1.6	1.8	1.7	1.8
NUMBER 145	LATITUDE	6.1	6.9	8.0	9.5	10.2	10.9	11.5	11.7	11.9	12.0
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	112.9	112.7	112.3	111.8	111.5	111.3	111.1	111.0	111.0	110.9
	DLONGITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	ALBEDO	18.5	23.8	29.4	32.3	34.9	35.3	36.9	39.5	34.0	34.8
	DALBEDO	.5	.4	.5	.5	.5	.6	.5	.7	.8	.9
NUMBER 147	LATITUDE	26.8	27.7	28.9	30.6	31.4	32.2	32.8	33.1	33.3	33.4
	DLATITUDE	3.1	3.1	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
	LONGITUDE	147.1	147.1	147.0	146.9	146.9	146.9	146.9	146.9	146.9	146.9
	DLONGITUDE	3.5	3.5	3.5	3.6	3.6	3.6	3.6	3.6	3.6	3.6
	ALBEDO	19.1	23.6	28.3	29.7	31.8	31.7	33.4	36.3	31.1	33.0
	DALBEDO	1.3	1.7	2.0	2.3	2.5	2.6	2.8	3.2	2.9	3.0
NUMBER 148	LATITUDE	9.9	10.9	12.0	13.6	14.5	15.2	15.8	16.0	16.2	16.3
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	146.0	145.8	145.6	145.3	145.1	145.0	144.9	144.9	144.8	144.8
	DLONGITUDE	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
	ALBEDO	19.4	24.2	28.9	30.9	33.6	33.6	35.1	38.0	33.0	35.4
	DALBEDO	1.1	1.4	1.5	1.7	1.8	1.9	2.0	2.2	2.1	2.3

Table A-1. Martian albedo (continued)

		WAVELENGTH									
		.60	.64	.70	.89	1.04	1.24	1.61	1.74	2.14	2.27
NUMBER 149	LATITUDE	-5.8	-4.8	-3.6	-1.9	-1.0	-1.2	.4	.6	.8	.9
	DLATITUDE	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.0	3.0	3.0
	LONGITUDE	147.1	146.3	146.5	146.0	145.8	145.6	145.5	145.4	145.4	145.3
	DLONGITUDE	3.4	3.4	3.4	3.4	3.3	3.3	3.3	3.3	3.3	3.3
	ALBEDO	19.2	23.8	26.9	31.8	34.3	34.7	36.3	39.0	32.6	34.8
	DALBEDO	1.2	1.5	1.7	1.9	2.0	2.1	2.1	2.5	2.1	2.4
NUMBER 150	LATITUDE	-21.9	-20.8	-19.4	-17.4	-16.5	-15.6	-14.9	-14.7	-14.4	-14.3
	DLATITUDE	3.6	3.5	3.5	3.4	3.4	3.4	3.3	3.3	3.3	3.3
	LONGITUDE	144.1	143.7	143.2	142.6	142.3	142.0	141.8	141.7	141.6	141.6
	DLONGITUDE	3.8	3.8	3.7	3.6	3.6	3.5	3.5	3.5	3.5	3.5
	ALBEDO	18.8	24.0	28.3	31.2	33.6	33.9	35.2	37.8	33.0	33.4
	DALBEDO	1.7	1.9	2.1	2.2	2.3	2.2	2.4	2.5	2.3	2.6
NUMBER 151	LATITUDE	-15.0	-13.9	-12.6	-10.7	-9.7	-8.9	-8.2	-8.0	-7.8	-7.7
	DLATITUDE	3.3	3.3	3.3	3.2	3.2	3.2	3.2	3.2	3.2	3.2
	LONGITUDE	129.3	129.0	128.8	128.4	128.2	128.0	127.9	127.9	127.8	127.8
	DLONGITUDE	3.3	3.3	3.3	3.2	3.2	3.2	3.2	3.2	3.2	3.2
	ALBEDO	17.7	22.6	27.6	30.3	32.7	32.7	33.9	35.6	31.1	31.2
	DALBEDO	1.1	1.0	1.2	1.2	1.3	1.2	1.2	1.3	1.4	1.4
NUMBER 152	LATITUDE	11.0	12.0	13.2	15.0	15.8	16.6	17.3	17.5	17.7	17.8
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	122.0	121.8	121.5	121.2	121.0	120.8	120.7	120.6	120.6	120.5
	DLONGITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	ALBEDO	19.0	24.3	29.6	32.6	35.2	35.5	36.9	39.0	34.0	33.7
	DALBEDO	.4	.5	.5	.6	.7	.7	.7	.8	1.0	1.3
NUMBER 153	LATITUDE	10.1	11.1	12.3	14.1	15.0	15.8	16.5	16.7	16.9	17.0
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	136.0	135.9	135.7	135.4	135.3	135.2	135.1	135.0	135.0	135.0
	DLONGITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.1	3.1
	ALBEDO	18.4	22.8	27.1	30.2	32.4	32.5	33.4	35.7	31.2	31.9
	DALBEDO	.7	.7	.9	1.0	1.0	1.1	1.1	1.1	1.2	1.7
NUMBER 154	LATITUDE	6.9	7.9	9.1	10.9	11.8	12.6	13.2	13.4	13.7	13.8
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	104.0	103.8	103.5	103.0	102.7	102.5	102.3	102.2	102.2	102.1
	DLONGITUDE	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
	ALBEDO	19.3	24.7	29.5	33.2	35.3	35.8	37.1	38.8	34.6	35.0
	DALBEDO	.8	.9	1.0	1.2	1.3	1.3	1.5	1.5	1.5	1.6
NUMBER 155	LATITUDE	12.0	12.7	13.5	14.7	15.2	15.8	16.2	16.4	16.5	16.6
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	90.0	89.5	88.9	88.1	87.6	87.0	86.9	86.8	86.7	86.7
	DLONGITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	ALBEDO	18.3	23.1	27.9	30.2	32.3	32.6	34.0	36.2	30.6	32.4
	DALBEDO	.6	.4	.5	.6	.6	.6	.7	.7	.9	1.0
NUMBER 156	LATITUDE	10.1	10.8	11.6	12.7	13.3	13.8	14.2	14.4	14.5	14.6
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	77.0	76.5	75.9	74.9	74.5	74.0	73.7	73.6	73.4	73.4
	DLONGITUDE	3.1	3.1	3.1	3.1	3.1	3.2	3.2	3.2	3.2	3.2
	ALBEDO	16.6	21.5	25.8	27.8	29.9	30.2	31.3	33.7	28.3	30.4
	DALBEDO	.6	.5	.6	.7	.8	.9	.9	1.0	.9	1.7
NUMBER 157	LATITUDE	12.0	12.6	13.4	14.5	15.1	15.5	16.0	16.1	16.2	16.3
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	62.0	61.4	60.6	59.5	58.9	58.4	57.9	57.8	57.6	57.5
	DLONGITUDE	3.5	3.5	3.6	3.6	3.6	3.7	3.7	3.7	3.7	3.7
	ALBEDO	14.1	18.7	21.4	23.0	24.8	25.3	26.4	28.7	24.3	26.7
	DALBEDO	.8	.9	1.1	1.3	1.4	1.6	1.7	2.0	1.8	2.0

Table A-1. Martian albedo (continued)

		WAVELENGTH									
		.60	.64	.70	.89	1.04	1.24	1.61	1.74	2.14	2.27
NUMBER	LATITUDE	-28.9	-28.0	-26.9	-25.3	-24.6	-23.9	-23.3	-23.1	-23.0	-22.9
159	DLATITUDE	3.9	3.9	3.8	3.7	3.7	3.7	3.6	3.6	3.6	3.6
	LONGITUDE	100.4	99.9	99.3	98.4	97.9	97.5	97.2	97.1	97.0	97.0
	DLONGITUDE	3.9	3.9	3.8	3.7	3.7	3.7	3.6	3.6	3.6	3.6
	ALBEDO	17.4	21.8	26.3	28.3	30.1	30.5	31.8	34.8	29.5	30.4
	DALBEDO	1.5	1.8	2.0	2.1	2.1	2.1	2.2	2.5	2.1	2.3
NUMBER	LATITUDE	-4.0	-3.3	-2.4	-1.1	-.4	.1	.6	.8	.9	1.0
160	DLATITUDE	3.1	3.1	3.1	3.1	3.1	3.1	3.0	3.0	3.0	3.0
	LONGITUDE	98.9	98.5	98.0	97.3	96.9	96.6	96.3	96.2	96.1	96.1
	DLONGITUDE	3.1	3.1	3.1	3.1	3.1	3.1	3.0	3.0	3.0	3.0
	ALBEDO	17.5	22.7	27.6	30.1	32.2	32.4	33.7	35.7	30.5	31.4
	DALBEDO	.6	.6	.7	.8	.7	.7	.8	.8	.9	.7
NUMBER	LATITUDE	29.0	29.3	30.7	32.1	32.7	33.3	33.9	34.0	34.2	34.3
161	DLATITUDE	3.2	3.2	3.2	3.2	3.2	3.2	3.3	3.3	3.3	3.3
	LONGITUDE	97.0	96.5	96.0	95.1	94.7	94.3	94.0	93.9	93.7	93.7
	DLONGITUDE	3.2	3.2	3.2	3.2	3.2	3.2	3.3	3.3	3.3	3.3
	ALBEDO	18.9	23.7	29.2	31.8	34.5	34.9	37.0	39.7	34.2	35.7
	DALBEDO	.8	.9	1.2	1.4	1.6	1.7	1.9	2.2	1.9	2.0
NUMBER	LATITUDE	13.0	13.8	14.7	16.1	16.7	17.3	17.8	18.0	18.2	18.3
163	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	114.0	113.6	113.2	112.6	112.3	112.0	111.7	111.7	111.6	111.5
	DLONGITUDE	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
	ALBEDO	18.9	24.2	28.8	31.5	33.9	34.4	35.9	39.0	32.9	34.7
	DALBEDO	.7	.9	1.1	1.3	1.3	1.4	1.5	1.7	1.6	1.9
NUMBER	LATITUDE	13.0	13.8	14.8	16.2	16.9	17.5	18.0	18.2	18.3	18.4
164	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	130.0	129.7	129.3	128.7	128.4	128.2	127.9	127.9	127.8	127.8
	DLONGITUDE	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
	ALBEDO	19.1	23.8	29.2	31.8	34.2	34.5	36.6	39.8	33.9	33.8
	DALBEDO	1.5	1.8	2.2	2.4	2.5	2.6	2.8	3.2	2.8	3.0
NUMBER	LATITUDE	-15.0	-14.2	-13.3	-12.0	-11.3	-10.7	-10.2	-10.1	-9.9	-9.8
170	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	340.0	339.6	339.1	338.4	338.0	337.6	337.4	337.3	337.2	337.1
	DLONGITUDE	3.7	3.7	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6
	ALBEDO	16.1	19.7	22.7	22.2	22.6	22.4	22.5	23.7	18.4	17.9
	DALBEDO	1.1	1.2	1.4	1.5	1.5	1.5	1.5	1.7	1.6	1.8
NUMBER	LATITUDE	-17.0	-16.2	-15.2	-13.8	-13.1	-12.5	-12.0	-11.8	-11.7	-11.6
171	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	350.1	349.7	349.2	348.5	348.1	347.8	347.5	347.4	347.4	347.3
	DLONGITUDE	3.5	3.5	3.5	3.5	3.5	3.4	3.4	3.4	3.4	3.4
	ALBEDO	15.0	18.2	21.0	20.1	20.7	20.0	20.1	21.0	17.1	17.2
	DALBEDO	1.0	1.1	1.1	1.1	1.1	1.1	1.1	1.3	1.2	1.5
NUMBER	LATITUDE	-4.9	-4.2	-3.2	-1.9	-1.2	-.6	-.1	.0	.2	.3
172	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	355.9	355.5	355.0	354.2	353.9	353.5	353.2	353.2	353.3	353.0
	DLONGITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	ALBEDO	13.5	15.2	17.2	16.1	16.4	16.3	16.8	16.5	14.7	14.9
	DALBEDO	.5	.6	.6	.5	.5	.5	.4	.5	1.1	.8
NUMBER	LATITUDE	9.0	9.7	10.6	11.8	12.4	13.0	13.5	13.6	13.8	13.9
173	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	341.0	340.5	339.9	338.9	338.4	338.0	337.6	337.5	337.3	337.3
	DLONGITUDE	3.3	3.3	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
	ALBEDO	18.7	23.4	28.7	30.9	33.0	32.9	33.8	36.8	30.6	32.0
	DALBEDO	.8	.9	1.2	1.4	1.6	1.6	1.7	1.9	1.8	1.8

Table A-1. Martian albedo (continued)

		WAVELENGTH									
		.60	.64	.70	.89	1.04	1.24	1.61	1.74	2.14	2.27
NUMBER 174	LATITUDE	-33.8	-32.7	-31.5	-29.7	-28.8	-28.1	-27.4	-27.2	-27.0	-26.9
	DLATITUDE	4.3	4.2	4.1	4.0	4.0	3.9	3.9	3.9	3.8	3.8
	LONGITUDE	347.5	347.2	346.9	346.4	346.2	346.0	345.8	345.7	345.6	345.6
	DLONGITUDE	4.6	4.5	4.4	4.3	4.2	4.2	4.2	4.2	4.1	4.1
	ALBEDO	16.1	16.6	20.8	20.7	21.2	21.3	21.7	23.1	17.8	20.0
	DALBEDO	2.3	2.5	2.7	2.5	2.5	2.5	2.5	2.7	2.2	2.4
NUMBER 175	LATITUDE	.1	.9	1.8	3.1	3.8	4.4	4.9	5.0	5.2	5.3
	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	343.0	342.5	342.0	341.2	340.8	340.4	340.1	340.0	339.9	339.8
	DLONGITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	ALBEDO	16.9	21.7	26.1	28.5	31.2	31.4	32.4	35.2	28.8	29.3
	DALBEDO	.9	1.0	1.1	1.4	1.5	1.6	1.6	1.7	1.6	1.8
NUMBER 180	LATITUDE	25.9	26.9	28.0	29.7	30.5	31.2	31.9	32.1	32.3	32.4
	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	36.0	35.9	35.6	35.3	35.1	35.0	34.9	34.8	34.8	34.8
	DLONGITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	ALBEDO	14.4	16.1	19.2	17.9	18.5	17.4	16.9	17.7	14.1	15.7
	DALBEDO	.9	1.1	1.3	1.2	1.3	1.3	1.3	1.5	1.8	1.7
NUMBER 181	LATITUDE	-12.0	-11.0	-9.8	-8.1	-7.3	-6.6	-6.0	-5.8	-5.5	-5.4
	DLATITUDE	3.3	3.3	3.2	3.2	3.2	3.2	3.2	3.1	3.1	3.1
	LONGITUDE	20.2	19.8	19.5	18.9	18.6	18.4	18.2	18.1	18.0	18.0
	DLONGITUDE	3.3	3.3	3.2	3.2	3.2	3.2	3.2	3.1	3.1	3.1
	ALBEDO	12.4	14.0	16.0	15.0	15.6	15.5	15.5	16.2	12.5	14.3
	DALBEDO	.6	.8	.7	.7	.7	.7	.7	.8	.5	.7
NUMBER 183	LATITUDE	-22.0	-20.9	-19.6	-17.7	-16.8	-16.0	-15.3	-15.1	-14.8	-14.7
	DLATITUDE	3.6	3.6	3.5	3.4	3.4	3.4	3.4	3.4	3.4	3.4
	LONGITUDE	20.0	19.7	19.3	18.8	18.5	18.3	18.1	18.0	18.0	17.9
	DLONGITUDE	3.6	3.6	3.5	3.4	3.4	3.4	3.4	3.4	3.4	3.4
	ALBEDO	11.6	13.2	14.0	13.4	14.3	14.0	13.8	14.9	11.3	11.8
	DALBEDO	.9	.9	.9	.8	.9	.8	.8	1.0	1.0	1.5
NUMBER 184	LATITUDE	4.1	5.1	6.3	8.0	8.8	9.6	10.2	10.4	10.6	10.8
	DLATITUDE	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
	LONGITUDE	45.0	44.8	44.5	44.1	43.9	43.7	43.5	43.5	43.5	43.4
	DLONGITUDE	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
	ALBEDO	15.8	20.0	22.5	23.3	25.4	25.3	26.0	27.8	23.5	22.7
	DALBEDO	1.3	1.5	1.8	1.7	1.9	2.0	2.1	2.4	2.4	2.4
NUMBER 185	LATITUDE	-6.0	-4.9	-3.7	-1.8	-.9	-.1	.6	.8	1.0	1.1
	DLATITUDE	3.2	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
	LONGITUDE	50.0	49.7	49.3	48.8	48.5	48.3	48.1	48.1	48.0	48.0
	DLONGITUDE	3.6	3.5	3.5	3.5	3.4	3.4	3.4	3.4	3.4	3.4
	ALBEDO	15.9	18.9	22.4	23.9	26.1	25.7	26.7	28.1	24.4	24.9
	DALBEDO	1.5	2.0	2.1	2.3	2.3	2.5	2.6	2.9	2.8	2.7
NUMBER 186	LATITUDE	-28.1	-26.8	-25.2	-23.0	-21.9	-20.9	-20.1	-19.9	-19.6	-19.5
	DLATITUDE	3.9	3.8	3.8	3.7	3.6	3.6	3.5	3.5	3.5	3.5
	LONGITUDE	45.8	45.3	44.6	43.7	43.3	43.0	42.7	42.6	42.5	42.5
	DLONGITUDE	4.3	4.2	4.1	3.9	3.9	3.8	3.8	3.8	3.7	3.7
	ALBEDO	14.7	15.8	18.6	18.3	18.7	18.5	18.9	19.1	16.4	16.7
	DALBEDO	1.9	1.9	2.2	2.0	2.0	1.9	1.9	2.1	1.9	2.3
NUMBER 187	LATITUDE	10.6	11.0	11.5	12.1	12.4	12.7	13.0	13.0	13.1	13.1
	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	287.0	285.9	284.4	282.2	281.1	280.1	279.2	278.9	278.5	278.4
	DLONGITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	ALBEDO	10.1	12.3	13.5	12.4	12.6	12.5	13.1	13.9	11.4	11.7
	DALBEDO	1.0	1.3	1.4	1.4	1.5	1.6	1.8	2.0	1.7	1.9

Table A-1. Martian albedo (continued)

		WAVELENGTH									
		.60	.64	.70	.89	1.04	1.24	1.61	1.74	2.14	2.27
NUMBER	LATITUDE	-3.8	-3.1	-2.3	-1.0	-.4	.1	.6	.7	.9	1.0
192	DLATITUDE	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1
	LONGITUDE	317.9	317.4	316.8	315.8	315.3	314.9	314.5	314.4	314.3	314.2
	DLONGITUDE	3.6	3.8	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
	ALBEDO	16.3	22.6	26.5	29.2	31.0	31.1	31.0	33.9	27.8	27.3
	DALBEDO	1.2	1.7	2.0	2.4	2.6	2.7	2.8	3.2	2.7	2.7
NUMBER	LATITUDE	-17.9	-17.1	-16.1	-14.6	-13.9	-13.3	-12.7	-12.6	-12.4	-12.3
194	DLATITUDE	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	LONGITUDE	331.9	331.6	331.1	330.4	330.1	329.8	329.5	329.4	329.4	329.3
	DLONGITUDE	3.3	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7
	ALBEDO	14.0	17.0	20.2	20.0	20.4	19.9	19.3	20.5	16.2	16.2
	DALBEDO	1.0	1.2	1.4	1.4	1.4	1.4	1.3	1.5	1.2	1.4
NUMBER	LATITUDE	-41.9	-40.6	-39.1	-37.0	-36.0	-35.2	-34.4	-34.2	-33.9	-33.8
195	DLATITUDE	5.1	4.9	4.8	4.6	4.5	4.4	4.3	4.3	4.3	4.3
	LONGITUDE	343.5	343.2	342.8	342.2	341.9	341.7	341.5	341.4	341.3	341.3
	DLONGITUDE	5.2	5.1	4.9	4.7	4.6	4.5	4.5	4.5	4.4	4.4
	ALBEDO	16.5	18.9	21.7	21.5	22.2	21.6	21.5	22.7	18.8	18.7
	DALBEDO	3.3	3.5	3.7	3.4	3.4	3.3	3.2	3.4	2.9	3.1
NUMBER	LATITUDE	17.9	18.5	19.2	20.3	20.8	21.2	21.6	21.7	21.9	21.9
197	DLATITUDE	4.1	4.1	4.1	4.1	4.1	4.2	4.2	4.2	4.2	4.2
	LONGITUDE	7.9	7.1	6.1	4.7	4.0	3.4	2.8	2.6	2.4	2.3
	DLONGITUDE	4.1	4.1	4.2	4.2	4.2	4.2	4.3	4.3	4.3	4.3
	ALBEDO	18.1	22.9	28.2	31.0	33.5	34.0	35.8	38.9	33.3	34.5
	DALBEDO	.5	.7	.9	1.1	1.2	1.3	1.4	1.6	1.5	1.6
NUMBER	LATITUDE	-17.0	-16.4	-15.6	-14.5	-13.9	-13.5	-13.0	-12.9	-12.8	-12.7
198	DLATITUDE	4.3	4.3	4.3	4.3	4.2	4.2	4.2	4.2	4.2	4.2
	LONGITUDE	24.9	24.1	23.2	21.9	21.2	20.7	20.2	20.0	19.9	19.8
	DLONGITUDE	4.4	4.4	4.3	4.3	4.3	4.2	4.2	4.2	4.2	4.2
	ALBEDO	13.5	16.6	18.8	17.9	18.8	18.7	19.7	21.2	17.2	17.8
	DALBEDO	.7	.8	.9	.9	.9	.9	.9	.9	1.0	1.1
NUMBER	LATITUDE	-17.0	-16.3	-15.5	-14.4	-13.8	-13.4	-12.9	-12.8	-12.7	-12.6
199	DLATITUDE	4.3	4.3	4.3	4.3	4.2	4.2	4.2	4.2	4.2	4.2
	LONGITUDE	25.1	24.4	23.5	22.2	21.5	21.0	20.5	20.3	20.2	20.1
	DLONGITUDE	4.4	4.4	4.3	4.3	4.3	4.2	4.2	4.2	4.2	4.2
	ALBEDO	13.6	16.0	17.9	17.3	17.8	17.8	18.7	20.2	16.9	17.1
	DALBEDO	.8	.8	.8	.7	.7	.8	.8	.8	.9	.8
NUMBER	LATITUDE	7.8	8.5	9.2	10.3	10.8	11.3	11.7	11.8	12.0	12.0
200	DLATITUDE	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
	LONGITUDE	35.0	34.3	33.5	32.3	31.7	31.2	30.7	30.6	30.4	30.4
	DLONGITUDE	4.2	4.2	4.2	4.2	4.1	4.1	4.1	4.1	4.1	4.1
	ALBEDO	17.9	22.3	26.3	28.0	29.7	29.5	30.8	33.1	28.0	29.1
	DALBEDO	.7	.6	.7	.7	.7	.7	.8	.9	.9	1.0
NUMBER	LATITUDE	15.0	15.7	16.7	18.0	18.7	19.3	19.8	20.0	20.2	20.3
202	DLATITUDE	4.0	4.0	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1
	LONGITUDE	313.1	312.7	312.3	311.6	311.3	311.0	310.8	310.7	310.6	310.6
	DLONGITUDE	4.0	4.0	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1
	ALBEDO	19.8	25.1	30.4	33.5	35.9	36.5	38.5	40.6	35.1	36.5
	DALBEDO	.3	.4	.5	.6	.6	.7	.8	.9	.8	.6
NUMBER	LATITUDE	33.0	33.8	34.9	36.4	37.2	37.9	38.4	38.6	38.6	38.9
203	DLATITUDE	4.4	4.5	4.5	4.6	4.6	4.6	4.7	4.7	4.7	4.7
	LONGITUDE	308.7	308.3	307.8	307.0	306.5	306.2	305.8	305.7	305.6	305.5
	DLONGITUDE	4.4	4.5	4.5	4.6	4.6	4.7	4.7	4.7	4.7	4.7
	ALBEDO	18.6	23.5	28.2	29.9	32.0	32.1	33.3	35.5	30.1	31.4
	DALBEDO	.9	1.2	1.6	1.8	2.0	2.1	2.3	2.5	2.2	2.3

Table A-1. Martian albedo (continued)

		WAVELENGTH									
		.60	.64	.70	.89	1.04	1.24	1.61	1.74	2.14	2.27
NUMBER 204	LATITUDE	8.9	9.6	10.6	12.0	12.7	13.3	13.0	14.0	14.2	14.3
	DLATITUDE	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
	LONGITUDE	335.0	334.7	334.3	333.8	333.5	333.3	333.1	333.0	333.0	332.9
	DLONGITUDE	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3
	ALBEDO	18.4	23.7	28.6	31.4	34.0	34.4	36.1	39.4	33.0	34.5
	DALBEDO	.8	.9	1.1	1.3	1.4	1.4	1.4	1.6	1.4	1.5
NUMBER 206	LATITUDE	23.0	23.8	24.8	26.3	27.0	27.7	28.3	28.4	28.6	28.7
	DLATITUDE	4.2	4.2	4.2	4.2	4.2	4.3	4.3	4.3	4.3	4.3
	LONGITUDE	328.0	327.8	327.5	327.0	325.8	326.6	326.4	326.3	326.3	326.2
	DLONGITUDE	4.3	4.3	4.3	4.3	4.4	4.4	4.4	4.4	4.4	4.4
	ALBEDO	19.3	24.3	29.6	32.3	34.9	35.4	37.1	40.6	34.5	35.4
	DALBEDO	.7	.9	1.2	1.3	1.4	1.5	1.6	1.8	1.5	1.6
NUMBER 207	LATITUDE	14.9	15.7	16.6	18.0	18.7	19.3	19.9	20.0	20.2	20.3
	DLATITUDE	4.0	4.0	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1
	LONGITUDE	287.0	286.5	285.9	285.1	284.6	284.2	283.9	283.7	283.6	283.6
	DLONGITUDE	4.5	4.6	4.6	4.6	4.7	4.7	4.7	4.7	4.8	4.8
	ALBEDO	10.9	13.0	15.0	13.9	14.6	14.8	15.6	16.7	13.3	13.9
	DALBEDO	.6	.8	1.0	1.1	1.2	1.2	1.2	1.3	1.1	1.1
NUMBER 208	LATITUDE	14.9	15.7	16.7	18.1	18.8	19.4	20.0	20.1	20.3	20.4
	DLATITUDE	4.0	4.0	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.1
	LONGITUDE	287.0	286.5	286.0	285.1	284.6	284.2	283.9	283.8	283.6	283.6
	DLONGITUDE	4.5	4.6	4.6	4.7	4.7	4.7	4.7	4.8	4.8	4.8
	ALBEDO	11.2	13.4	15.4	15.0	16.0	16.4	17.4	18.8	15.0	16.6
	DALBEDO	.7	.8	1.1	1.1	1.2	1.3	1.2	1.3	1.2	1.2
NUMBER 209	LATITUDE	2.1	2.9	3.8	5.3	6.0	6.6	7.1	7.3	7.4	7.5
	DLATITUDE	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
	LONGITUDE	289.0	288.6	288.2	287.6	287.2	286.9	286.7	286.6	286.5	286.5
	DLONGITUDE	4.5	4.5	4.5	4.6	4.6	4.6	4.6	4.6	4.6	4.6
	ALBEDO	12.0	14.0	15.9	15.1	15.8	16.1	16.3	17.6	14.5	15.4
	DALBEDO	.8	.9	1.0	1.0	1.1	1.2	1.2	1.3	1.2	1.5
NUMBER 210	LATITUDE	28.0	28.8	29.9	31.5	32.3	33.0	33.6	33.8	34.0	34.1
	DLATITUDE	4.3	4.3	4.3	4.4	4.4	4.4	4.5	4.5	4.5	4.5
	LONGITUDE	328.1	327.9	327.6	327.2	327.0	326.8	326.6	326.6	326.5	326.5
	DLONGITUDE	4.4	4.4	4.4	4.5	4.5	4.5	4.5	4.5	4.5	4.5
	ALBEDO	18.9	24.5	29.8	32.9	35.4	35.8	37.8	40.7	35.1	36.0
	DALBEDO	.8	1.1	1.4	1.6	1.8	1.9	1.9	2.2	2.0	2.0

APPENDIX B

GLOSSARY OF PHOTOMETRIC AND POLARIMETRIC TERMINOLOGY

Albedo	See geometric albedo, Bond albedo, normal albedo.
Blackbody	A body in complete thermodynamic equilibrium with its surroundings, which in turn implies detailed balancing of all associated atomic and molecular processes. A blackbody is completely defined by one parameter, the equilibrium temperature, and radiates according to Planck's law.
Bolometric	An adjective implying radiometric data (rather than photometric) integrated over all wavelengths. A bolometric magnitude is thus a measure of total power, and a bolometric albedo is a mean albedo over all wavelengths, unaffected by atmospheric or photometric system absorptions and response.
Bond (sometimes Russell-Bond or spherical) albedo	The ratio of the power (flux) reflected in all directions by a body to the power incident upon it in a collimated beam. It is the fraction of incident solar flux that is NOT absorbed.
Brightness temperature	The temperature that a blackbody would have to have in order to emit the same power (flux) that is actually measured at the wavelength in question.
Degree of polarization	By definition, the difference $I_{\max}$ less $I_{\min}$ divided by the sum $I_{\max}$ plus $I_{\min}$. $I_{\max}$ is the maximum intensity of the polarized beam which lies in the plane containing the electric vector and the direction of propagation. $I_{\min}$ is perpendicular to that plane.
Detailed photometry	Point by point photometry of an extended source.
Geometric albedo	The ratio of <u>mean</u> luminance of a body at full phase (phase angle zero) to the luminance of an "intrinsically white" <u>plane</u> surface normal to the source of illumination (Sun). An "intrinsically white" surface scatters all of the power incident upon it (absorbing none) and does so according to Lambert's cosine law. Such a surface is also called a perfectly diffusing surface.

Illuminance	The photometric equivalent of irradiance, the power-per-unit solid angle and unit-projected area <u>falling upon a surface</u> within the passband of a photometric system. In the narrowest sense, this refers only to the passband of the human eye, but in astronomy, the broader sense is often used, applying the terminology to any defined photometric system.
Integrated photometry	Photometric study of an entire body as a unit, as opposed to detailed photometry.
Inversion angle	The phase angle at which the degree of polarization changes from negative to positive.
Irradiance	Radiometric term for power-per-unit solid angle and unit-projected area <u>falling upon a surface</u> .
Lambert surface	A surface which has the same radiance when viewed from any angle.
Lambert's cosine law	A surface radiating (or reflecting or transmitting) an amount of flux per unit area and unit solid angle proportional to the cosine of the angle between the surface normal and the direction of observation is said to follow Lambert's cosine law. Such a surface is a Lambert surface.
Luminance	The photometric equivalent of radiance, the power-per-unit solid angle and unit-projected area <u>leaving a surface</u> within the passband of a photometric system. In the narrowest sense, this refers only to the passband of the human eye; but, in astronomy, the broader sense is often used, applying the terminology to any defined photometric system.
Luminance equator	The intersection of the phase plane with the surface under study.
Luminance latitude	The angle between the phase plane and the normal to the surface at the point of observation. See Figs. 3 and 5 in the text.
Luminance longitude	The angle of observation (reflection angle) projected into the phase plane. See Figs. 3 and 5 in the text.
Magnitude	A logarithmic unit of electromagnetic flux, ancient in origin, used in astronomy. In modern usage, one magnitude is equivalent to a ratio of 2.512 in flux. See the text for a complete definition of the system.

Normal albedo	The ratio of luminance of a point at zero phase to the luminance of an intrinsically white plane Lambert surface normal to the illumination. This is the photometric equivalent in detailed photometry to geometric albedo in integrated photometry. See geometric albedo; also the main text.
Opposition effect	An enhanced brightness occurring for phase angles $ \alpha \leq 10^\circ$. For example, in the B-passband, linear extrapolation to zero phase would give $B_0(0) = -0.21$ as Mars' magnitude, where, in fact, it is $B_0 \approx -0.31$.
Percent polarization	Just 100 times the degree of polarization. Sometimes permil polarization, written ‰ and equal to 1000 times the degree of polarization is also used.
Phase angle	Astronomically, the object (body) centered angle between the source of illumination (the Sun) and the observer (detector). See Fig. 3. In local photometry, the angle between source (Sun) and detector measured at the observed point. See Fig. 5.
Phase coefficient	The phase function of a body is often presented in the form of a polynomial expansion with the phase angle as the argument. The linear coefficient is often called the phase coefficient (and over the limited range of phase angle available for Mars it is an adequate representation without additional terms).
Phase function	The ratio of power (flux) scattered at phase angle α to that scattered at zero phase. The phase function is often given as a cubic polynomial, in tabular form, or as a polar graph.
Phase integral	The ratio of power (flux) scattered in all directions to that scattered at zero phase, per unit solid angle. The phase integral multiplied by the geometric albedo equals the Bond albedo.
Phase plane	The Sun - object - observer plane, the plane containing the phase angle. See Figs. 3 and 5.
Photometric data	Flux data convolved with the response of a particular detector system. In the strictest sense, photometric data is that received by a "standard" human eye, but, astronomically, the term is applied to any calibrated combination of filters, detectors, etc.
Photometric function	The ratio of the radiance factor to the normal albedo for a point on a sphere. The photometric function is a function of three parameters: the phase angle, angle of incidence, and angle of observation; or, alternately, the phase angle, luminance longitude, and luminance latitude.

Radiance	Radiometric term for power-per-unit solid angle and unit-projected area <u>leaving a surface</u> .
Radiance (luminance) coefficient	The ratio of radiance (luminance) observed to that of a white plane Lambert surface at the same inclination to the source of illumination.
Radiance (luminance) factor	The ratio of radiance (luminance) observed to that of a white plane Lambert surface normal to the source of illumination.
Radiometric data	Flux data given in absolute units, deconvolved of any photometric system response curve. These units can be either astronomical (magnitude) or physical (watts) and may still refer to a particular region of the spectrum, rather than be integrated over all wavelengths (bolometric data).
Solar constant	The irradiance (power-per-unit area) from the Sun at a distance of one astronomical unit.
Spectral irradiance	Radiometric term for power incident per unit area and wavelength upon a surface.
Spectral radiant exitance	Radiometric term for power-per-unit area and wavelength coming from a surface.
Stokes parameters	Four parameters which give a complete description of polarized light. See van de Hulst (1957) or Shurcliff (1962) for details.

3.3 RADAR PROPERTIES

INTRODUCTION

Earth-based planetary radar observations have substantially improved our knowledge of the orbits of the terrestrial planets, refining their ephemerides, and providing data of importance in basic research, as well as in the planning of missions to these planets. Radar observations have helped to provide a more reliable value for the radius of Mars, a value confirmed by the Mariner flybys (see Section 1). Radar studies have provided extensive information on Martian topography in equatorial latitudes, as well as on the dielectric constant and roughness of the Martian surface.

Radar astronomy is simple in basic concept, but it is complex in execution and theory. The paragraphs immediately following discuss the concepts (it is hoped) in sufficient depth to understand the observational results. No attempt is made to offer detailed derivations of formulas, as these are available in many texts.*

3.3.1 BASIC CONCEPTS OF RADAR ASTRONOMY

In radar astronomy, a signal is transmitted with the highest available power and the narrowest possible beamwidth in order to concentrate as much power as possible on the target. The flux decreases proportionate to the square of the distance from the transmitter. The angular width of the transmitted beam is much greater than any planetary target, so only a small fraction of the transmitted power strikes the target and is scattered back toward Earth. The target returns also grow weaker as the square of the distance and are received by the largest possible collecting area (antenna). The basic radar equation relating power transmitted P_t to power (signal) received P_s is

$$\frac{P_s}{P_t} = \frac{G_t A_r \sigma}{(4\pi r^2)^2}$$

where

G_t is gain of the transmitting antenna (compared to an isotropic radiator)

A_r is area of the receiving antenna

σ is the target scattering cross-section

r is the target distance

Typically, for the largest radar facilities this ratio is about 10^{-23} for Mars, even when the planet is near a perihelic opposition and as near as it ever comes

*See (for example) Radar Astronomy by Evans and Hagfors (1968).

to Earth. Thus, in radar astronomy, as in radio astronomy, the reception of weak signals is the general rule, and improvements in the signal-to-noise ratio have come about through larger antennas, increased transmitter power, and more sensitive (lower noise) receivers.

The transmitted frequency is limited to wavelengths longer than about 1 cm, due to increasing absorption in the Earth's atmosphere caused by water vapor and oxygen at the shorter wavelengths. At wavelengths greater than about 20 m, signals are scattered by the Earth's ionosphere. Within the available frequency range (1 cm to 20 m), the choice is usually at the shorter wavelength end, because antenna gain increases inversely as the square of the wavelength for a given antenna area, at least to a point where imperfections in the surface of the antenna begin to approach the wavelength transmitted.

The signal may be transmitted continuously (CW) at powers up to several hundred kilowatts, or it may be pulsed with a peak power of many megawatts. Either type of transmission may be additionally modulated or coded; to obtain range resolution with continuous wave (CW) radar, and to remove range ambiguities with pulsed radar.

The signal-to-noise ratio may be improved by time integrations of the received signal. Since the round-trip time for a signal transmitted to Mars is more than six minutes, even when Mars is closest to Earth, it is possible to transmit for at least six minutes and then listen (receive) for six minutes without confusion, even using only one antenna. For Mars, there is a complication introduced by the relatively rapid rotation of the planet. Long integration times inevitably result in a loss of surface resolution.

All results discussed in this section are the product of monostatic radar experiments, experiments in which the angle of incidence of the transmitted signal is the same as the angle of reflection (or backscattering) of the received signal. The angular size of Earth as seen from Mars is so small (<1 arc min at closest approach) that even experiments using different transmitting and receiving antennas are still essentially monostatic. A true bistatic experiment could be carried out by transmitting from Earth and receiving from a nonterrestrial site or spacecraft.

3.3.2 CROSS-SECTION AND REFLECTIVITY

Fundamental Concepts

The target or total radar cross-section σ is usually defined as 4π times the ratio of the power-per-unit solid angle scattered back toward the transmitter, to the power-per-unit area (power density) striking the target (Westman, 1956).*

*This classical definition assumes a monostatic radar system is used. With a bistatic radar, the radar cross-section σ_b of the illuminated target is a measure of the energy scattered in the direction of the receiver (Skolnik, 1962).

The radar cross-section is a characteristic of the target and is a measure of its size as seen by the radar (Skolnik, 1962), and has the dimensions of area (m^2). * The radar cross-section depends not only upon the actual size and orientation (the geometrical cross-section), but also on the reflectivity and the roughness of the target.

The radar cross-section σ of a spherical body, such as a planet in first approximation, is expressed mathematically in two different ways, relative to its geometrical cross-section πR^2 (where R is the planetary radius):

- 1) first formulation: $\sigma = \rho_o g \pi R^2$
- 2) second formulation: $\sigma = \bar{\rho} G \pi R^2$

where the dimensionless parameters ρ_o , g , $\bar{\rho}$, and G are the "reflectivity under normal incidence," the "directivity," the "spherical (or Bond) reflectivity," and the "gain in backscattering," respectively. Only the first formulation is useful in describing monostatic measurements of Mars, and it will be considered in more detail.

The reflectivity ρ_o is the classical Fresnel power reflection coefficient for a plane homogeneous surface when a plane wave is incident upon it normally:

$$\rho_o = \left\{ \frac{1 - \sqrt{\frac{\mu_o}{\mu} \frac{\epsilon}{\epsilon_o} + i \frac{s}{\omega \epsilon_o}}}{1 + \sqrt{\frac{\mu_o}{\mu} \frac{\epsilon}{\epsilon_o} + i \frac{s}{\omega \epsilon_o}}} \right\}^2$$

where the symbols are

s = electrical conductivity

ϵ = permittivity } with subscript $_o$ referring to free space values;
 μ = permeability } therefore, ϵ/ϵ_o and μ/μ_o are relative permittivity
 (dielectric constant) and relative permeability

ω = angular frequency - related to frequency f or free space wavelength λ_o , respectively, by $\omega = 2\pi f = 2\pi c/\lambda_o$, where c = velocity of light

i = imaginary unit

Thus, it is seen that generally ρ_o depends upon wavelength and upon the electromagnetic characteristics of the reflecting surface material. If the material is a perfect dielectric ($s = 0$ and $\mu = \mu_o$), then ρ_o becomes

*The radar cross-section often is expressed in fractional terms of the ratio $\sigma/\pi R^2$ where R is the radius of the target, or as a percentage, throughout this section.

$$\rho_o = \left[\frac{1 - \sqrt{\frac{\epsilon}{\epsilon_o}}}{1 + \sqrt{\frac{\epsilon}{\epsilon_o}}} \right]^2$$

Therefore, for a perfect dielectric, ρ_o is independent of wavelength λ and only depends upon the dielectric constant $k = \epsilon/\epsilon_o$. Generally, rocks and soils in a very dry environment have a very low conductivity s . Therefore, provided the relative permeability μ/μ_o is close to unity (when only minute amounts of magnetic material are present), this last equation can be used with fair approximation.* Its application seems to have met with success in the case of the Moon. It may be less valid for Mars, which is closer to the asteroidal belt and possibly has larger amounts of magnetic meteoritic material on its surface. However, for lack of firm knowledge, this equation will be used later to derive an approximate value of the effective dielectric constant.

The directivity g is determined by the ability of the actual (rough spherical) surface to backscatter favorably toward the illuminating source (monostatic radar). The actual returns are compared with those obtained from a perfectly smooth spherical (isotropic) surface, for which $g = 1$. Directivity g should not be confused with gain (Rea et al., 1964). For an arbitrary rough sphere, g can be calculated, provided the statistics of height deviations and surface slopes are known. For example, the case of a smooth undulating sphere was treated by Hagfors (1964), who gave the approximation: $g \approx 1 + \alpha^2$, where α is the rms surface slope (α is small; e.g., $\alpha \sim 0.1$ at λ 1 m).

The distance between Earth and Mars constantly changes as the two planets move around the Sun. The frequency transmitted from Earth therefore returns at a slightly (Doppler) shifted central frequency f' . The amount of this shift is accurately known and is usually automatically compensated for by means of a computer-controlled adjustment of the receiver. Far more important is the Doppler spread introduced by the rotation of Mars. Because the rotating target is a sphere (approximately), its illuminated hemisphere returns the wave in the form of fine semiannular slices of its surface, with constant frequency f' aligned parallel to the plane formed by the axis of apparent rotation and the line-of-sight. To the radar observer, the disk to be explored may be divided into a series of parallel lines or narrow strips of constant Doppler shift Δf , symmetrical about the central frequency f' line or strip, which has zero shift ($\Delta f = 0$) and represents the apparent rotation axis (see Fig. 1). The spread Δf , corresponding to each line, is proportional to its distance from the f' line (axis), and the maximum spread $\Delta f_{\max}$ occurs for returns from the two most distant lines, tangent to the limbs. This is given by $\Delta f_{\max} = 2\omega' \cdot R/\lambda_o'$, where ω' is the apparent rotation rate (rad/sec), R the radius of the planet, and $\lambda_o' = c/f'$ the center wavelength.

Because of the fast rotation of Mars, the rotational Doppler effect (i.e., $\Delta f_{\max}$ at the limbs) is much larger than the orbital Doppler effect. The total

* ρ_o may depend upon λ , since longer wavelengths penetrate to greater depth where denser soils will have higher dielectric constant.

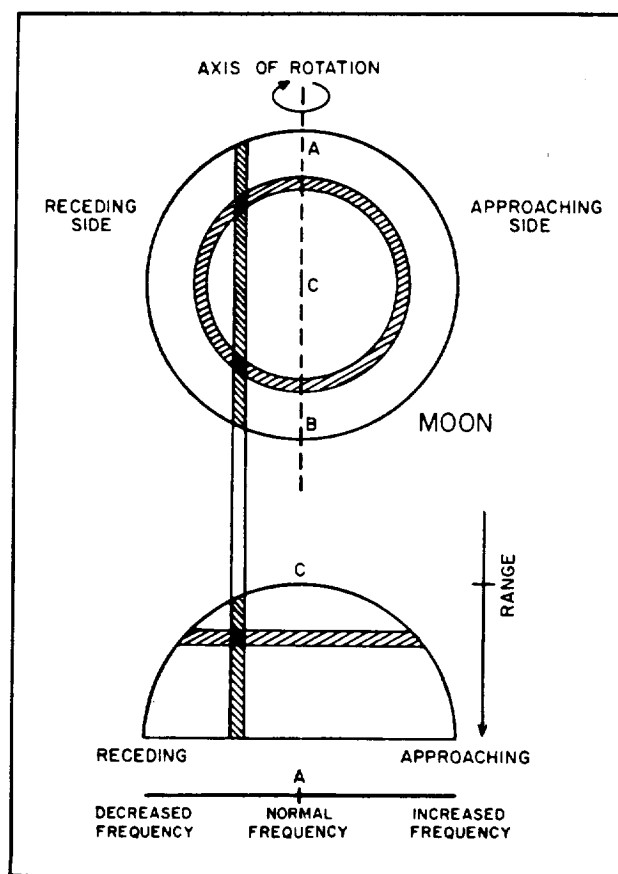


Fig. 1. The system of constant delay rings and doppler shift strips on the disk (Evans and Hagfors, 1968).
(Only one ring and one strip are indicated.)

limb-to-limb bandwidth $B (= 2\Delta f_{\max})$ is given in Table 1 for several commonly used radar frequencies.

Table 1. Doppler spread, or "limb-to-limb bandwidth" B of the Martian echo, as a function of operating frequency f ($\approx f'$) or wavelength λ_0 ($\approx \lambda'_0$).

f , MHz	λ_0 , cm	B , Hz
7,840	3.8	~23,500
2,388	12.5	7,670
700	43	2,200
430	70	1,280

An additional contouring of the planet is introduced by the finite velocity of light. When a short pulse of duration or width τ transmitted to a planet, and echoes are received at a later time T , those echoes must come from an annulus (or ring) whose edge-on width is $c\tau/2$. Furthermore, if the first echoes (from the subradar point) arrive at a time T_0 , and the echo of interest arrives at a time $t = T - T_0$ later, then the distance between the plane of the annulus and the subradar point is $ct/2$. These rings are also plotted in Fig. 1. The area of the annulus is independent of its location (or delay time t) and is equal to $\pi R c \tau$, determined only by pulse duration τ , with R the radius of the planet, and c the speed of light. The angle of incidence i (equal to the angle of back-scattering ϕ) is practically constant over the annulus area (if the pulses are very short, order of μsec), and is related to the delay time t by the interchangeable relations (with unique correspondence):

$$i = \phi = \arccos \left(1 - \frac{ct}{2R} \right)$$

or

$$t = \frac{2R}{c} (1 - \cos i)$$

It can be seen that the combination of Doppler strips and delay rings decomposes the entire planet into a set of "resolution cells" symmetric about the apparent equator. Each cell is specified by its set $(t, \Delta f)$ of delay-resolution coordinates. There is an inherent North-South ambiguity (since one strip intersects a ring twice), but this may be resolved either in time through rotation of the surface, or spatially by using a narrow beamwidth (as has been done for the Moon). The present radar capability does not permit narrow beamwidth operation at the distance of Mars. Although it is possible theoretically to produce reflectivity maps of the entire disk, only areas close to the subradar points have been studied to date, on Mars. A set of "range-gated" spectra (spectra separated according to delay rings) taken by Goldstein et al. (1970) is shown in Fig. 2.

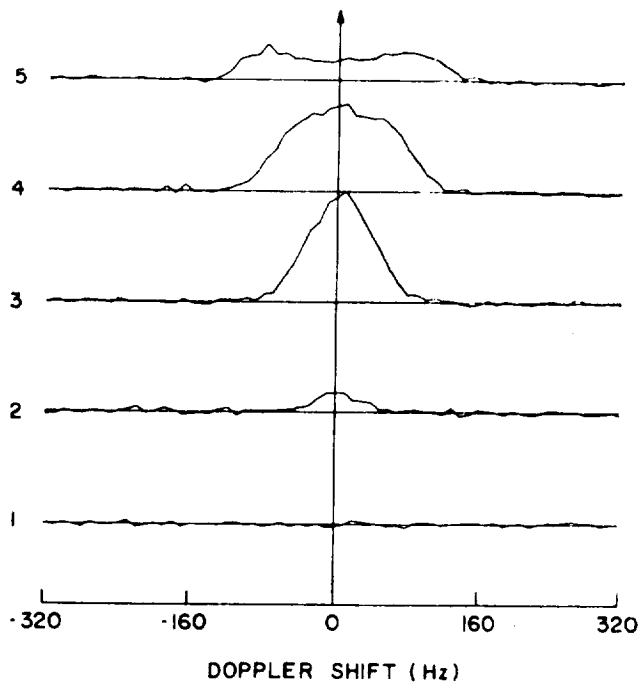
Observation Techniques

Usually continuous waves (CW) are employed to measure the radar cross-section of a planet.* The actual measurement may be performed either directly, by using a radiometer (measuring total power), or indirectly, by integration of the Doppler spectrograms.

The total radar cross-section represents the echo power reflected from the entire disk; that is, it must total both quasi-specular and diffuse scattering portions of the echo, and may be expressed: $\sigma = \sigma_s + \sigma_d$. At short (centimeter) wavelengths, the quasi-specular returns have a higher (peak) intensity, but total power is greater in the diffuse component of the cross-section. At longer (meter)

*Pulses may be employed to measure σ , but the pulse length (duration τ) must be as long as the radar depth of the planet ($2R/c$), so that a full hemisphere is illuminated at one time to obtain the total cross-section. The radar depth for Mars is 22.6 msec.

a) AERIA



b) CANDOR

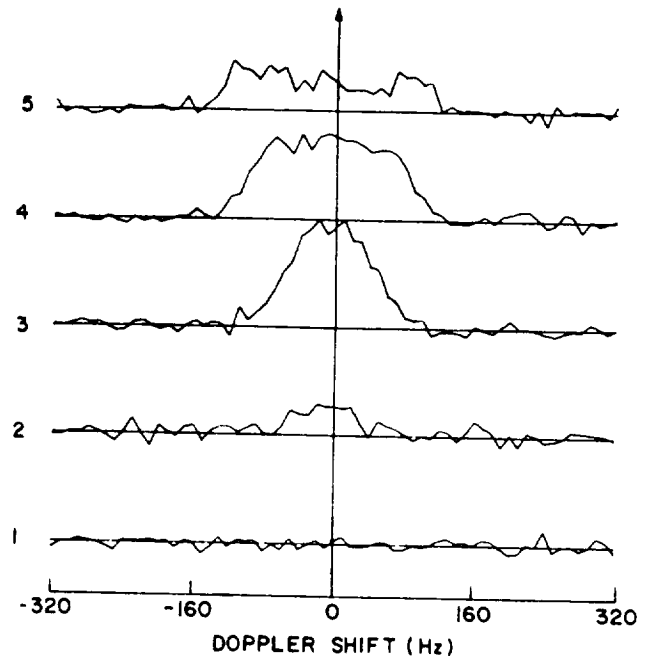


Fig. 2. Samples of range-gated frequency power spectra set (Goldstein et al., 1970).

wavelengths, it appears likely* that the opposite is true. Good measurements of total cross-section can only be obtained with a high signal-to-noise ratio. Early measurements were dominated by the quasi-specular component.

A radar observing run consists of a succession of alternate transmissions and receptions, usually continuing as long as the planet is conveniently above the horizon. Transmission is made in a circular polarization mode in order to avoid the problems of Faraday rotation (of a linearly polarized wave traversing our ionosphere). Reception of the echo waveform from Mars, because of the weak signal-to-noise, has, so far, only been made in the sense of circular polarization, 180° opposite in phase to that transmitted. This 180° return corresponds to specular reflections from a smooth surface. Only the so-called "polarized" component of the echo has been received from Mars. When radar capability improves, it will be possible to receive the same 'sense' as transmitted; that is, the weaker so-called "depolarized (or cross-polarized) component," which is the depolarization product of surface roughness.

Antenna aiming is done automatically by computer. The central frequency of the receiver is also automatically adjusted to compensate for Doppler shift introduced by the relative velocity of the observing station and the target (Mars).

*If Mars behaves like the Moon, which appears likely as discussed later.

Because of the fast rotation rate of Mars itself, the subradar point travels some 100° in longitude during one night of observation, maintaining nearly the same circle of latitude. Because the terrestrial rotation is some 37 minutes faster than Mars, several weeks are necessary in order to cover a full 360° in longitude over Mars from a single station. (There is considerable overlap of sectors visible in successive nights.) After several weeks, the subradar point also will be circling at a somewhat different latitude, the excursion in latitude being given by the change in areocentric declination (D_E in American Ephemeris) of the Earth. Figure 3 shows these excursions for the observing periods of the experiments since 1963.

Early Radar Observations (1963 and 1965)

The first successful radar observations of Mars were made by two groups, during the unfavorable opposition of early 1963: In the United States, by a JPL group (Goldstein and Gilmore, 1963), at 12.5-cm wavelength; and in the Soviet Union, by a Radioengineering and Electronics Institute group (Kotelnikov et al., 1963), at 43-cm wavelength. Both groups reported a cross-section varying directly with the surface presented: σ varied from 2 to 13 percent as the subradar point circled the planet at 13° - 14° N latitude. Kotelnikov et al. obtained an average of 7 percent, similar to that of the Moon. Their results are considered unreliable, however, because of very low signal-to-noise ratio (~ 1.5 - 2.5). Goldstein and Gilmore, covering a full rotation of Mars, produced the first radar brightness map along the 13° N parallel--which visually is practically all bright

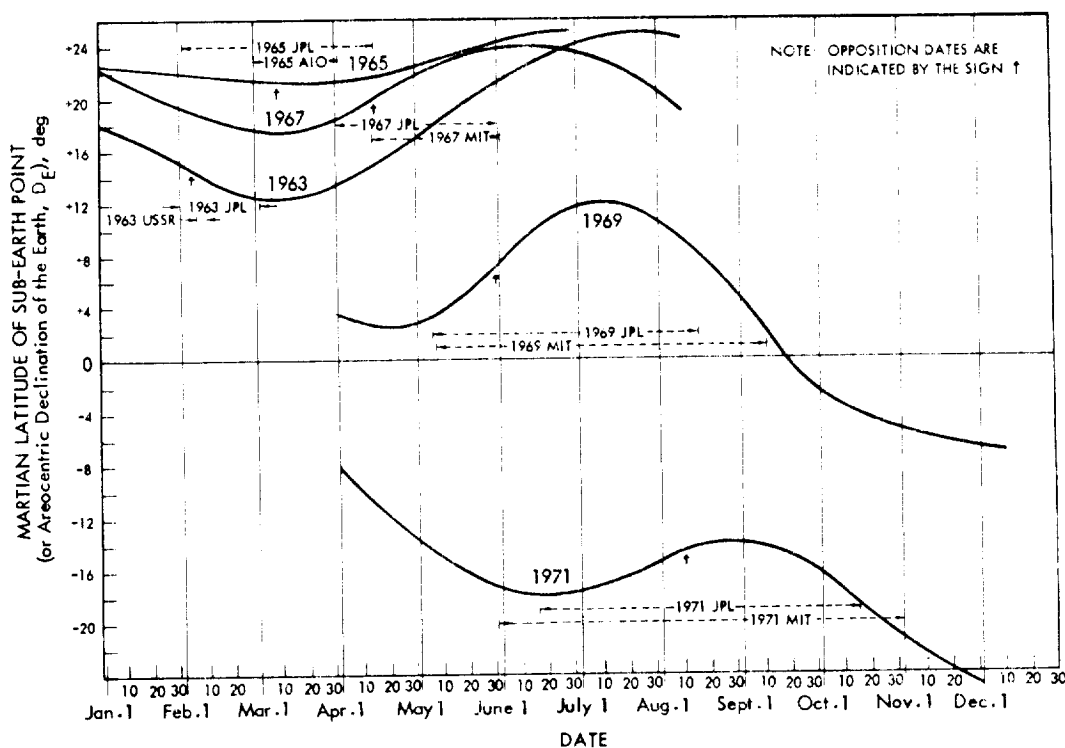


Fig. 3. Excursions in Martian latitude of the subradar point for the 1963 to 1971 apparitions of Mars.

area-- and they noted that the visually dark Syrtis Major appeared bright to radar. They also found, from their average Doppler spectrogram, that Mars is somewhat smoother than Venus.

After 1963, the Russians appear to have discontinued radar observations of Mars. From that time through 1970, reports have come only from investigators in the United States. At the opposition of March 1965, Goldstein (1965), with improved radar equipment, secured 36 Doppler spectrograms, each an average of many runs, from successive longitude intervals near the 21°N latitude circle. Some areas, such as Trivium Charontis-Cerberus, showed high, narrow peaks, indicating very smooth, strong reflecting areas. Others (e.g., Nodus Laocoontis) had a wider, lower peak, suggesting a rougher, but still strong, reflecting area. Surprisingly, the northern tip of Syrtis Major showed no strong echo. The large Amazonis desert was a poor reflector, but the poorest reflecting areas were the dark features Ascraeus Lacus and Albis Lacus. On the whole, Mars was found to be significantly smoother than Venus at $\lambda 12.5$ cm.

At MIT, Evans et al. (1965) derived a cross-section average of 14 percent by summing the echoes obtained over four nights of observations at $\lambda 23$ cm.

Investigations which may be considered the forerunner of more modern observations were conducted by Dyce, et al. (1967), at Arecibo Observatory in 1965 (AIO). Using the 1000-foot antenna at $\lambda 70$ cm, they measured an average radar cross-section of 7 percent, varying with rotation between 3 to 13 percent, as the subradar point latitude remained within 1° of 22°N . These results are very similar to the first results of 1963 at 13°N - 14°N latitude.

Dyce et al. (1967) illuminated Mars with a stream of short (4 and 19 msec) phase-coherent pulses, and analyzed the echoes by the delay-Doppler method. The resultant cross-section measurements confirmed that dark areas crossing the central meridian gave strong echoes, but the correlation was noted to be imperfect. The "significant differences in precise alignment" were attributed to large-scale slopes passing the subradar region. Their plot of the radar cross-section versus longitude at the 22°N parallel was compared against a simplified strip map (see Fig. 4). An example of this comparison indicates that Syrtis Major corresponds to a local minimum between two high peaks, while Trivium Charontis lies slightly off an isolated high "peak."

Secondarily, the delay-Doppler analysis for Mars definitely established the presence of two components of scattering. These were (1) a prominent, narrow-band, which was somewhat variable with the longitude (the "central peak" of the spectrum). This was attributed to the quasi-specular reflections from the central region of the disk; and (2) a low-level, relatively broad-band, less variable component which corresponded to the large, more distant surrounding regions extending almost halfway to the limbs. Dyce et al. presumed the latter component to be due to diffuse scattering.

By refining their analysis through measurements of bandwidths and shifts of the central peaks, they calculated that the large-scale "smooth" slopes responsible for the asymmetry of the spectral peaks varied from about 10° to less than 3° .

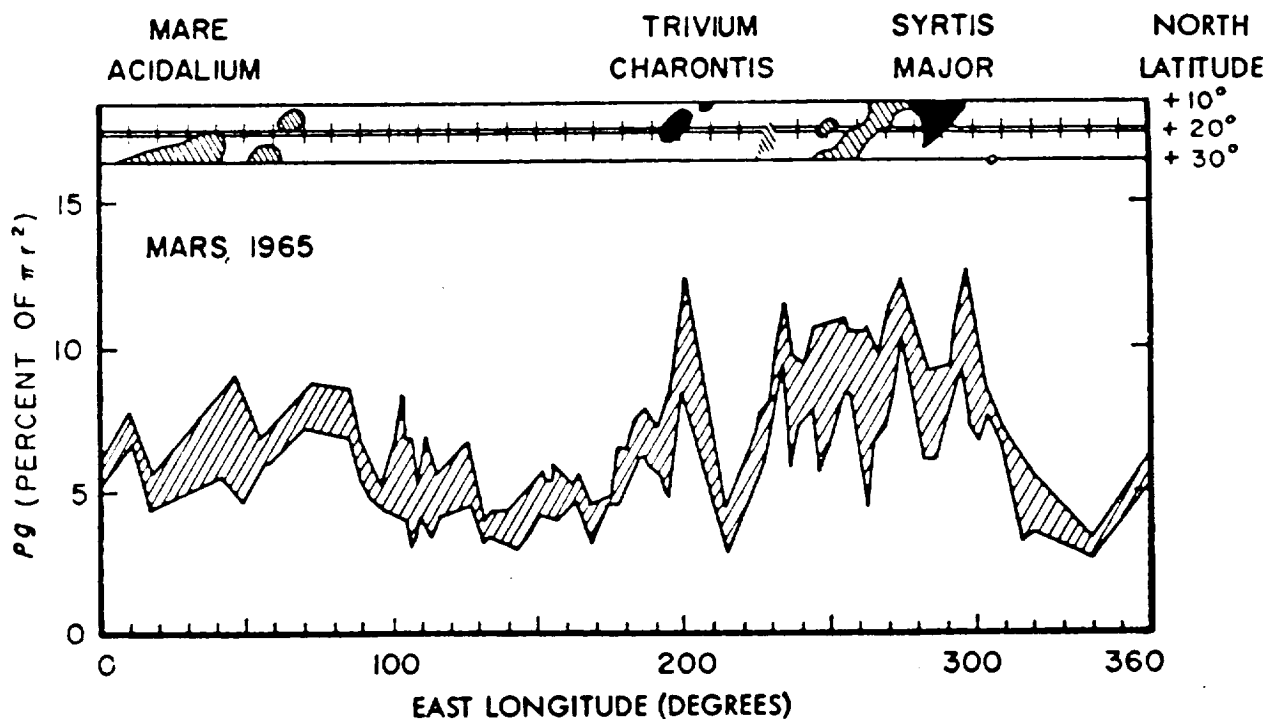


Fig. 4. The variation of the radar cross-section near the 22°N latitude as a function of the longitude of the central meridian of the visible disk as obtained at 70-cm wavelength (Dyce et al., 1967).

Recent Radar Observations (1967 and 1969)

Carpenter (1967) transmitted $\lambda 12.5$ cm CW at Goldstone, using an 85-foot antenna for transmission and the 210-foot antenna for receiving the signal returns. Many Doppler-broadened spectrograms of Mars were obtained during April and May 1967, scanning the 21°N latitude area of Mars; see Fig. 5(a). The maximum bandwidth of 3.7 kHz excluded only half of the total spectrum (approximately 30° in longitude). Utilizing the 60 composite (average) spectra obtained at every 5° longitude around Mars, Carpenter measured the radar cross-section variations, and attempted to estimate surface roughness from the half-power widths. His results are plotted in Fig. 5(b) as a fractional cross-section versus areocentric longitude, with specific Martian features also noted.

The mean $\sigma/\pi R^2$ is 0.063, but remarkable variations ranging from 0.015 to 0.123 were found along the explored area of 21°N parallel. Carpenter found no clear relationship between the visual and radar-derived appearance of Mars.

Pettengill et al. (1969), in 1967, and Rogers et al. (1970), in 1969, in a conjoined effort at MIT's Lincoln Laboratory, explored Mars at $\lambda 3.8$ cm by using unmodulated CW for cross-section and Doppler spectrograms determination. These

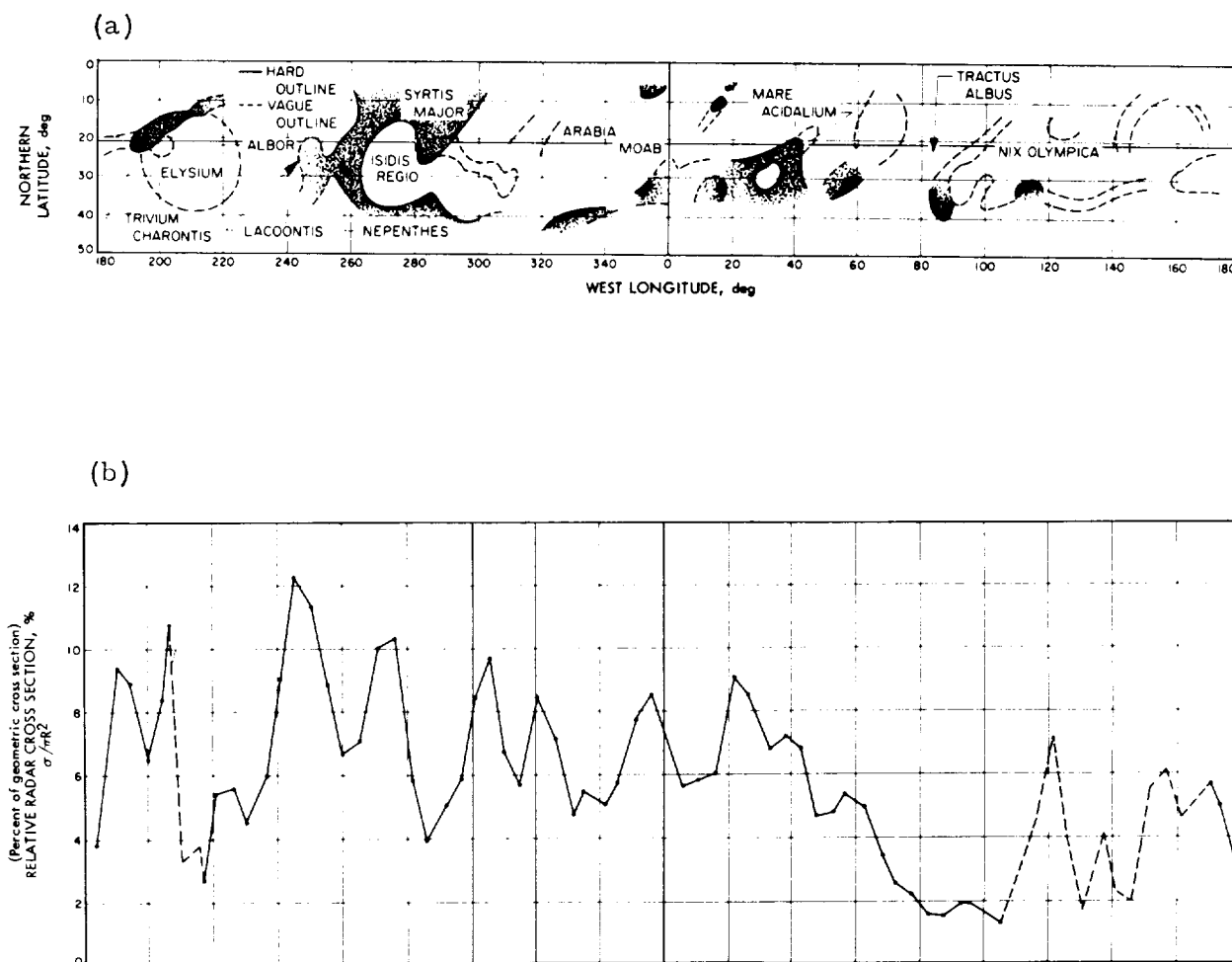


Fig. 5. Radar cross-section variation with longitude near the 21°N parallel of latitude, as obtained at 12.5-cm wavelength (Carpenter, 1967).

were spectrally analyzed by the "one-bit autocorrelation technique" of Goldstein (1961). The sampling frequency in 1969 provided a small window only 4.8-kHz wide, permitting 120-Hz resolution (as compared to 1 kHz in 1967). This proved sufficient to resolve the narrow central peak in the quasi-specular portion of the echo. This frequency resolution corresponded to 0.5° in longitude on Mars near the subradar point; however, because of the rapid rotation of Mars during the 10-minute integration period (required to improve the signal-to-noise ratio), the frequency resolution was degraded to $\sim 2^\circ$ in longitude. The spectrum obtained was best-fitted by a theoretical spectrum based on Hagfors' exponential scattering law. This fit required adjustment of three parameters: slope parameter C (rms slope $\approx 1/\sqrt{C}$), frequency offset Δf from ephemeris-predicted "zero frequency shift" (effect of a tilted subradar region), and radar cross-section σ_s . The cross-sections obtained are plotted in Fig. 6. Additional cross-sections were obtained as a "byproduct" of topographic studies using phase-coded CW. These are presented in Fig. 7 for four latitudes from 3° to 22° N.

The small radar cross-section values obtained (0.02 - $0.04 \pi R^2$) pertain only to the central region of the disk around the subradar point, because of the narrow-band windows used in both the CW (4.8-kHz) and phase-coded (1-kHz) measurements, compared to the 23.5-kHz limb-to-limb Doppler spread. Thus, a substantial portion of the total echo power from the full disk, or total radar cross-section, was excluded. The measured relative radar cross-section is almost exclusively due to the quasi-specular portion of the echo.

According to Pettengill et al. (1969), the quasi-specular portion of the echo, at $\lambda 3.8$ cm, contributes from less than 0.006 to about $0.05 \pi R^2$ to the total cross-section of Mars, while the diffuse portion contributes a "background" cross-section about $0.1 \pi R^2$, largely independent of longitude. The total for the entire disk averages $0.11 \pi R^2$, or $g\rho_0 = 0.11$, at $\lambda 3.8$ cm, according to them.

Using this value ($\sigma = 0.11 \pi R^2$) as a basis, these investigators recalculated the average total cross-section values, which previous observers would have obtained, taking account of the limitations due to too narrow spectral acceptance of the receiver (CW window), or poor delay resolution from too short pulses. Table 2 lists these results for comparison. The new values generally are in fair agreement with the older ones actually reported. Exceptions are those of Evans et al. (1965) and especially of Kotelnikov et al. (1963).

In contrast to topography, the fractional radar cross-section, or the reflectivity ρ_0 if $g = 1$, exhibits abrupt variations with latitude as well as longitude. At present, it is unknown whether the variations are due to local surface roughness, electromagnetic properties of the material (dielectric constant), or surface geometry.

If conductivity and permeability effects are neglected, an effective dielectric constant k may be derived from the fractional radar cross-section $\sigma/\pi R^2$, or reflectivity ρ_0 (assuming $g = 1$), through the relation

$$k = \left[\frac{1 + \sqrt{\rho_0}}{1 - \sqrt{\rho_0}} \right]^2$$

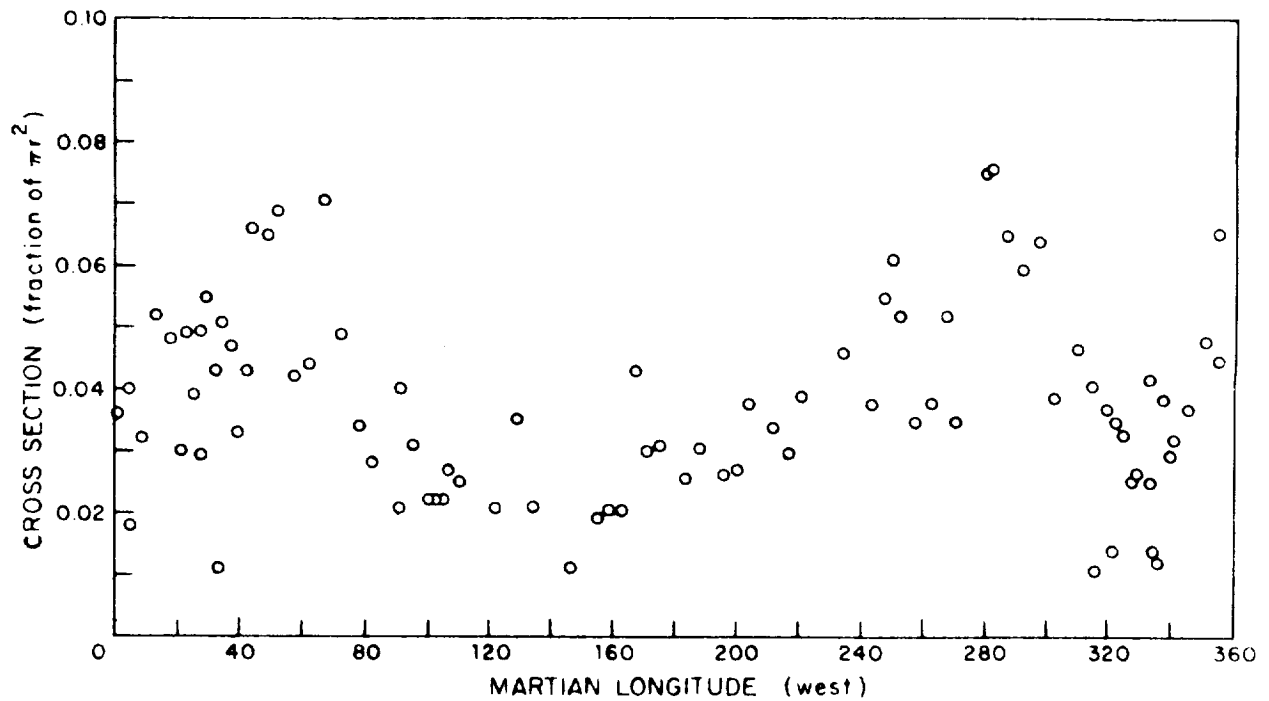


Fig. 6. Relative radar cross-section variation with longitude as inferred from CW echo-Doppler spectrograms at 3.8 cm wavelength (bandwidth 4.8 kHz) (Lincoln Laboratory, 1970).

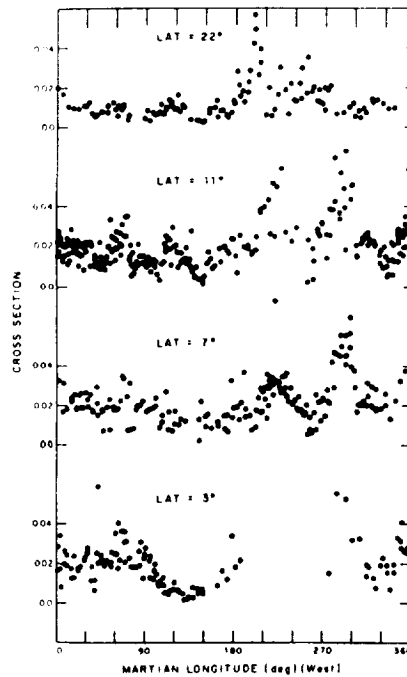


Fig. 7. Relative radar cross-section variation with longitude near four latitudes, as inferred from phase-coded (ranging) measurements at 3.8 cm wavelength (bandwidth 1 kHz) (Lincoln Laboratory, 1970).

Table 2. Comparison of radar cross-sections obtained by various observers (Pettengill et al., 1969).

Observer	Date	Martian latitude, deg	Radar wavelength, cm	Normalized ^a receiving bandwidth	Observed radar cross section			Calculated ^b average cross section (πa^2)
					max (πa^2)	min (πa^2)	avg (πa^2)	
Goldstein and Gillmore (1963), JPL	1963	13°N	12.5	0.053	0.07	0.01	0.032	0.037
Kotel'nikov et al. (1963), USSR	1963	14°N	~40	0.0016	0.15	0.03	0.07	0.0014
Goldstein (1965); Sagan et al. (1967), JPL	1965	21°N	12.5	0.48	0.16	0.04	0.087	0.097
Evans et al. (1965), MIT/LL	1965	21°N	23	0.125	--	--	0.14	0.067 ^c
Dyce et al. (1967), AIO	1965	22°N	70	0.20	0.13	0.03	0.07	0.072 ^c
Pettengill et al. (1969), MIT/LL (CW observations only)	1967	19°N	3.8	1.00	0.14	0.09	0.11	0.11
				0.04	0.05	0.02	0.031	0.034

^aNormalized to the appropriate limb-to-limb bandwidth.

^bCalculated from the indicated normalized bandwidth of the receiver on the basis of the average cross section and (typical) scattering law observed at 3.8 cm.

^cA factor associated with resolution in delay has also been taken into account in these calculations.

^dUnfortunately, the 1969 measurements are not included in this table.

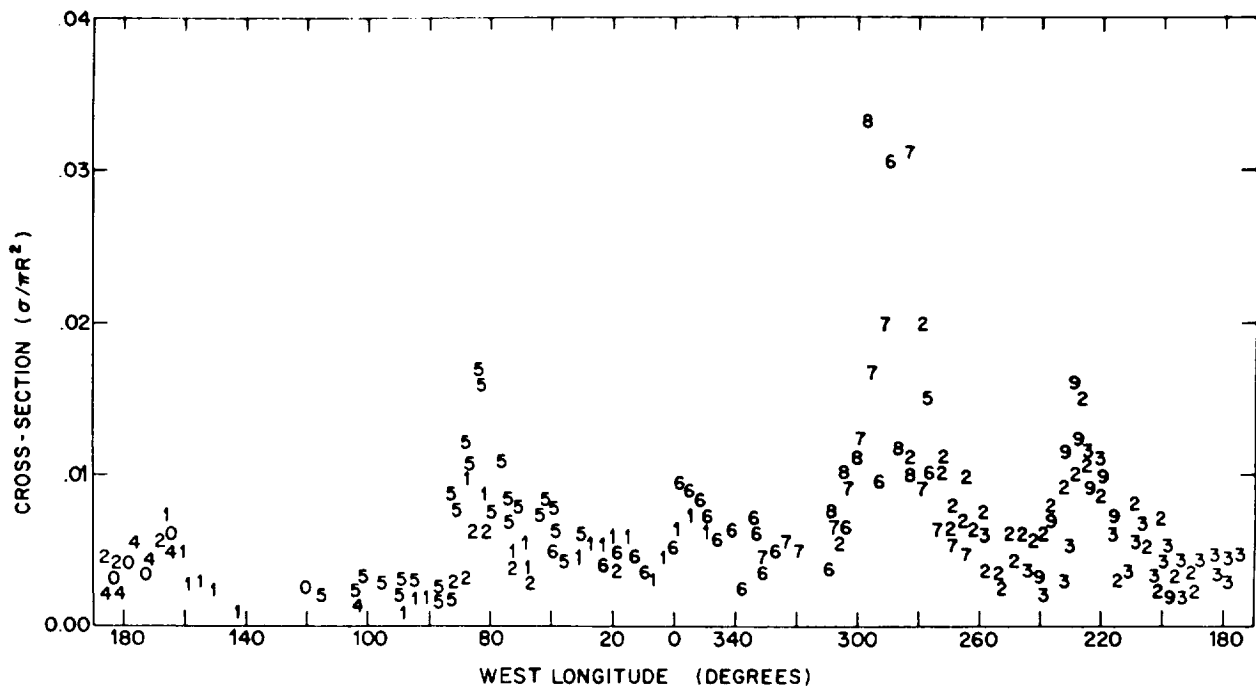
Using $\rho_o = 0.0915$ (Pettengill et al., 1969) leads to $k = 3.5$, an intermediate value between that of the Moon (~3) and of Venus (4.5 at decimeter wavelengths). This implies that the material is loosely compacted, like sand.

At JPL in 1969, Goldstein et al. (1970) performed delay-Doppler analysis on the echos from subradar areas. They used coded CW at a wavelength of 12.5 cm, because they were primarily interested in topography. They looked at only the central 640 Hz of the 7600-Hz limb-to-limb bandwidth, but had 10-Hz resolution within the frequency range studied. The cross sections shown in Fig. 8 are therefore relative cross-sections for local areas.

3.3.3 ANGULAR SCATTERING AND ROUGHNESS

Fundamental Concepts

Information on the average surface roughness of the planetary targets is contained in the angular backscattering law specified by the average echo power $\bar{P}(\phi)$ versus angle of incidence (or reflection, since $i = \phi$). $\bar{P}(\phi)$, also called the "angular power spectrum," is usually derived from measurements of $\bar{P}(t)$, the echo power versus delay function, through the unique $\phi \leftrightarrow t$ correspondence, discussed on pages 5 and 6, when short pulses (<1 msec) are transmitted. The function $\bar{P}(\phi)$ actually averages the echo power at a given incidence angle, as contributed by the delay annulus corresponding to that angle. Therefore, $\bar{P}(\phi)$ represents a backscattering law which implicitly assumes a uniformly rough surface over the spherical target.



Note: The digits refer to latitudes according to the code:
 3=3°N, 4=4°N, ... 0=10°N, 1=11°N, and 2=12°N.

Fig. 8. Relative radar cross-section variation with longitude near several latitudes 3°-12°N (Goldstein et al., 1970).

An alternative, but more involved, procedure for obtaining $\bar{P}(\phi)$ is by derivation from the average echo power frequency spectrum $\bar{P}(\Delta f)$, usually written $\bar{P}(f)$ (a "Doppler spectrogram"), through one of two mathematical transformations available. These are (1) the Fourier-Bessel transformation as used by Hagfors, Nanni, and Stone (1968), and (2) the inverse Abel transformation, as used by Carpenter (1964). The latter transformation has also been employed for Mars by Pettengill et al. (1969), at λ 3.8 cm.

Radar echoes $\bar{P}(t)$ or $\bar{P}(\phi)$ from the terrestrial planets are composed of two parts: (1) the "quasi-specular" portion--a strong central highlight from the subradar region, which is attributed to near-normal reflections from large smooth surface elements; and (2) the "diffuse scattering" portion--a much weaker, or subdued "background" from the surrounding concentric regions, as far as the limbs, which is attributed to scattering from a large number of smaller-scale elements (sometimes called the "diffuse scatterers").

There are two kinds of "surface roughnesses" associated with scattering. One kind (diffuse scattering) is due to the small surface elements, such as rocks strewn on the surface or buried in shallow depth. The larger of these elements gives some normal backscatter, while the very small, and especially the angular elements, can also give returns by diffractive scatter and multiple

reflections. The stronger echoes (quasi-specular) are from the frontal area and large surface elements (those normal to the line of transmission).

Surface roughness is usually measured statistically by the rms slope pertaining to a certain horizontal scale size. Slopes on a planet can be derived from the radar data by means of several procedures, each yielding an rms slope on scales larger than the wavelength. The three procedures which were applied to Mars radar data are as follows:

Backscattering Model Fitting (for very small-scale slopes)

The central, quasi-specular portion of the echo may be approximated by a theoretical backscattering law of either gaussian or exponential form, as was done for the Moon. From experience, it was found that the following law, successfully developed by Hagfors (1964) for the Moon, also provides a good fit for Mars:

$$P(\phi) \propto (\cos^4 \phi + C \sin^2 \phi)^{-3/2}$$

where C is a parameter related to the rms surface slope. For large C (as in the case of Mars) the rms slope $\approx 1/\sqrt{C}$. This law assumes a uniform exponential distribution of surface slopes over the target (uniform roughness), and applies to a horizontal scale size of about 1 to 10 times the probing wavelength λ . (For further elaboration, consult the Lunar Scientific Model, JPL Document 900-278, Radar section.) The particular parameter C value, providing the best fitting curve (by least squares of residuals) to the planet's angular power spectrum $\bar{P}(\phi)$, yields the rms small-scale slope. No applicable theoretical model is available for the diffuse scattering portion of the echo.

Power Spectrum Frequency Offset Measurement (for intermediate slopes)

The power spectra obtained from analysis of CW returns may show an asymmetry of frequency displacement of the central peak from the expected (ephemeris-predicted) "zero-frequency shift" position ($\Delta f = 0$). This frequency offset may be interpreted as the effect of an overall general tilt of the subradar region. This offset is then equal to

$$\Delta f = \frac{2f'}{c} \cdot \frac{dr(t)}{dt} = \frac{2f'}{c} \cdot \omega' \frac{dh}{dL}$$

where f' is the center frequency, c is the velocity of light, and $r(t)$ is the distance of the subradar point from the center of mass of the target (Mars). The quantity r is a function of time t because of the planet's (apparent) rotation at rate ω' . The apparent rotation differs somewhat from the true rotation of Mars, because of the relative motion of Mars and the radar equipment. The quantity L is longitude, while h is height (which also varies with time, of course).

The obtainable tilt or E-W slope dh/dL refers to a much larger horizontal scale (60-120 km, if $L = 1^\circ$ - 2°) than the slope inferred from backscattering modeling parameter C . With an improved signal-to-noise ratio, finer resolution can be obtained with this technique.

Height Profile Differentiation (for large-scale slopes)

The height-versus-longitude profiles obtained from ranging measurements permit, by simple differentiation procedure (i.e., taking derivative of topography), derivation of E-W slopes on a still larger scale (e.g., 300-600 km from $L = 5^\circ$ - 10°). If a contour map of heights is available for several latitude belts, the slopes in other directions may be similarly derived.

Experimental Results

Pettengill et al. (1969), have provided a complete 0° - 90° angular back-scattering curve $\bar{P}(\phi)$ for Mars at their operating wavelength of 3.8 cm. They derived $\bar{P}(\phi)$ from a representative echo power frequency spectrum $\bar{P}(f)$ by using the Bessel transformation, see Fig. 9 (a and b).

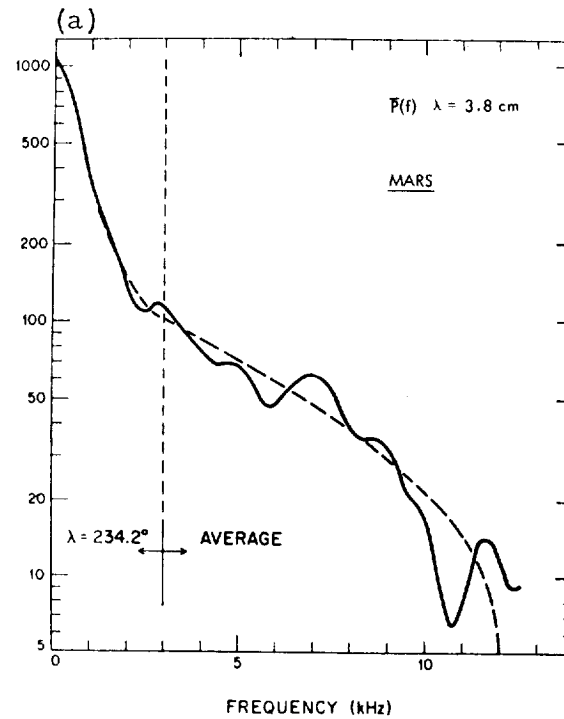
Figure 9(b) compares the scattering behavior of Mars with that of the Moon, Venus, and Mercury, utilizing their $\bar{P}(\phi)$ curves at a wavelength of 3.8 cm. The fast drop of the Mars curve shows that Mars is definitely smoother than Venus, which, in turn, is smoother than either Mercury or the Moon.

Using all available data (MIT at 3.8 cm, JPL at 12.5 cm, and AIO at 70 cm), Zachs and Fung (1969) derived the $\bar{P}(\phi)$ curves at three wavelengths from the planetary-averaged $\bar{P}(f)$ curves, which they also computed by using Abel and Bessel mathematical transformations as a crosscheck. Their results are shown in Fig. 10, where, for convenience, the processed $\bar{P}(f)$ curves are also shown. They note that the 70-cm data pertained only to a small sector (208° - 221°) of Martian longitude. Therefore, the derived 70-cm curve $\bar{P}(\phi)$ is regional, and cannot readily be compared to the averaged planetary curves obtained at 12.5 and 3.8 cm. The 12.5- and 3.8-cm curves do, however, show variation with wavelength, invalidating the statement, by Dyce et al. (1967) and Pettengill et al. (1969), that the Martian scattering law does not vary with wavelength. These two curves exhibit scattering similar to that observed on the Moon. Indeed, it appears that the fraction of echo power in the diffuse portion $\bar{P}(\phi)$ increases as the wavelength decreases. The 12.5- and 3.8-cm curves are characteristic of planetary smoothness, while the 70-cm curve is either anomalous or indicates regional roughness significantly different from that obtained for the other curves.

Interpretation

The surface slopes for the north equatorial belt, derived by the MIT, Lincoln Laboratory group in 1969, utilizing the three procedures outlined in the earlier paragraphs on Fundamental Concepts, are as follows:

- 1) On a small scale of about 1 - 10λ , corresponding to parameter $C = 300$, giving best fit using Hagfors' backscattering model, an rms slope of 3.3° was derived.
- 2) On the large scale of about 120 kms, corresponding to the $\sim 2^\circ$ longitude resolution of the CW measurements, an rms slope of 0.5° was derived.



(by Bessel transform)

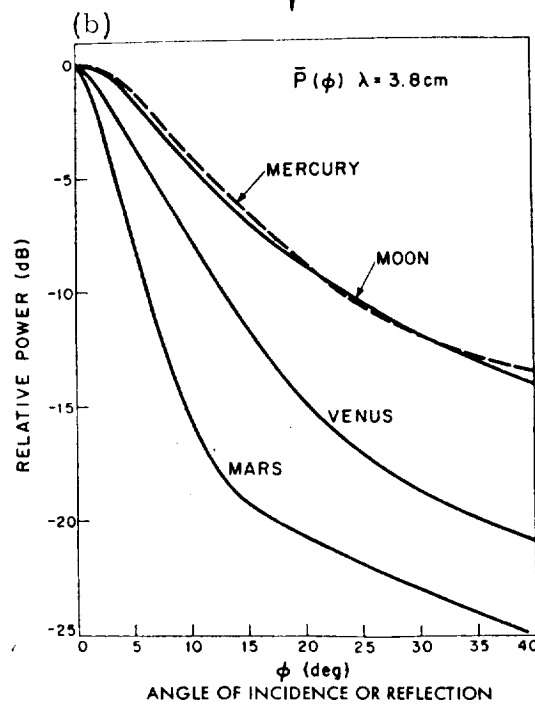


Fig. 9. Frequency power spectrum for Mars converted by Bessel transformation for comparison with the Moon, Mercury, and Venus
Top (a): Pettengill et al (1969). Bottom (b): Evans (1969).

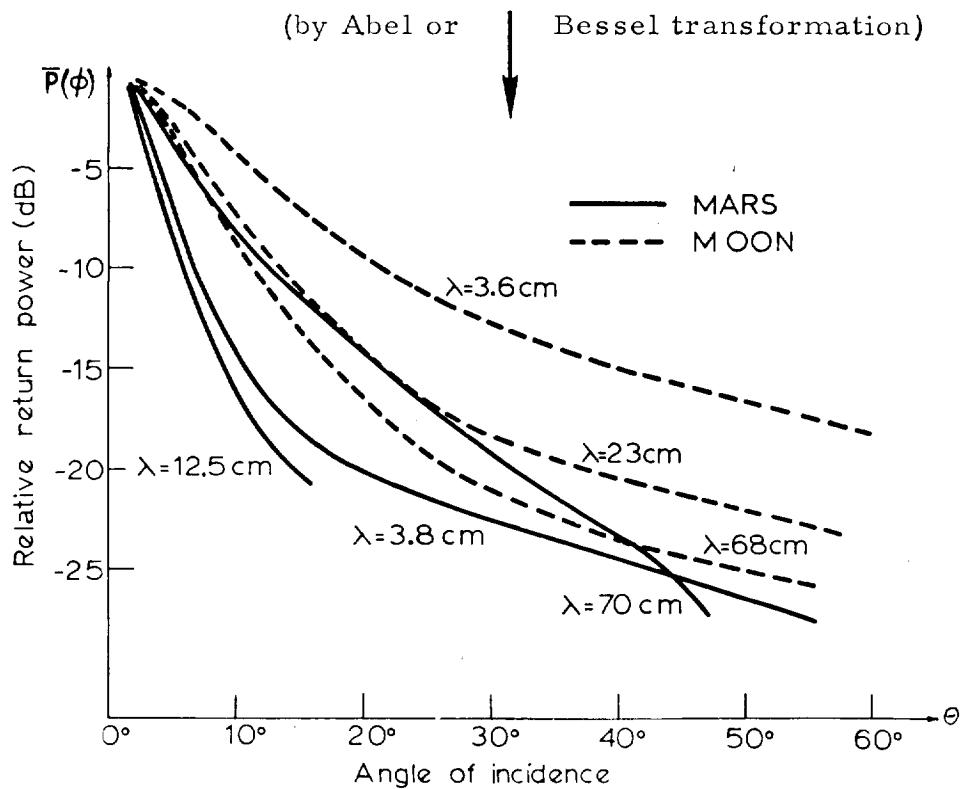
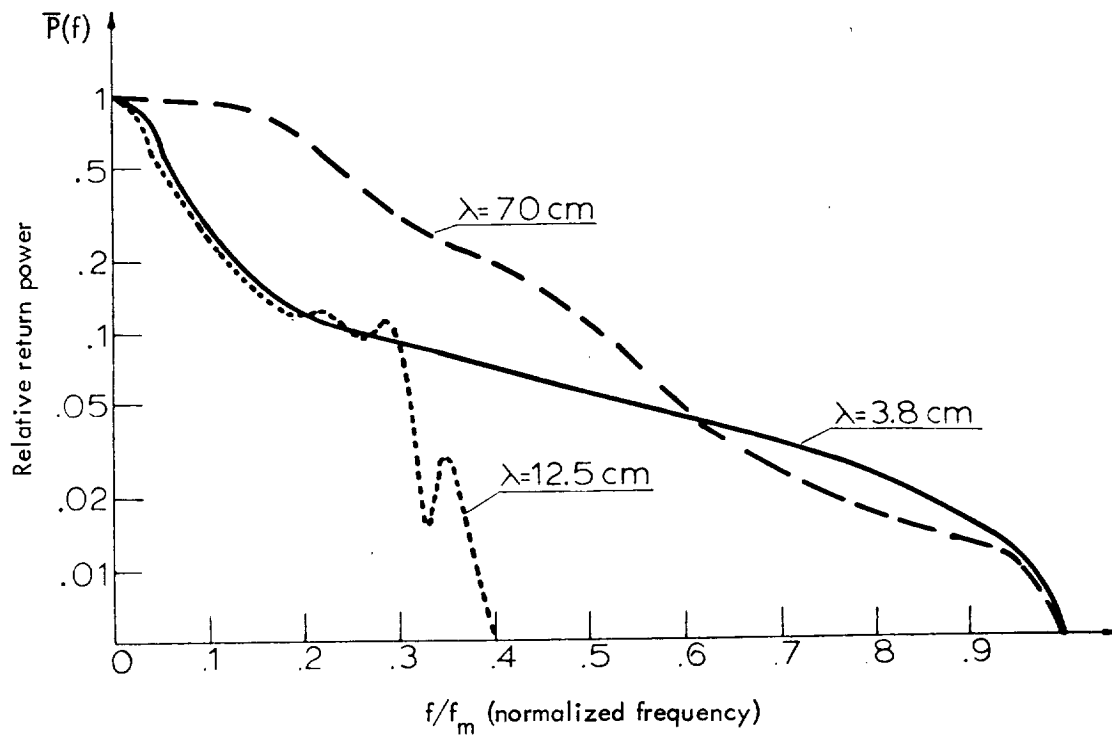


Fig. 10. Average doppler spectrograms (top) and angular backscattering curves (bottom) for Mars at several wavelengths (Zachs and Fung, 1969).

- 3) On the still larger scale of about 180 kms, corresponding to the $\sim 3^\circ$ longitude resolution of the ranging measurements, an rms slope of 0.3° was derived.

3.3.4 TOPOGRAPHY

Fundamental Concepts

The fundamental method used to measure Martian topography is the round-trip delay technique. By very accurate timing of the strong central echo, using either narrow pulses or phase-coded CW, it has been possible to obtain elevation differences. Typically, the measurement made refers to the mean return from a small spherical front cap a few areocentric degrees in size.

In such topographic ranging measurements, it is necessary to know the accurate relative orbits (or ephemerides) of both planets. It is also necessary to accurately determine the center, the rotation rate, radius, and the degree of flattening (shape). Since the (equatorial) radius and orbit of Mars are not accurately known, ranging measurements are also used to obtain (by solution of simultaneous equations) better determination of these quantities.

The topography may be checked at "closure points," when available. Closure points are defined as a pair of altitude (or delay) observations* made at very close or coinciding locations on the planet. However, these must be made at different times, separated by approximately one or more synodic rotations of the two planets (i.e., ~ 40 days in the case of Mars). Any important discrepancy noted between these two altitudes leads to a correction of the relative orbits (or ephemerides) and serves as a check on the topography.

The zero level of topography, as used on the illustrations and (for one latitude strip around the planet), is obtained arbitrarily as the average of heights. When many such strips have become available for each accessible latitude over the years 1965 to 1975, a grand average of heights will furnish a better zero level.

Experimental Results

An early attempt was made in 1965 by Dyce et al. (1967) at Arecibo to derive topographic information for Mars. They were only able to set an upper limit of about 15 km for the greatest elevation difference, at about 17°N latitude.

The MIT efforts of Pettengill et al. (1969) in 1967 and Rogers et al. (1970) in 1969 used 3.8 cm phase-coded CW for their round-trip delay topographic studies. The 1969 work involved an elaborate least-squares fit to a theoretical delay profile, based on Hagfors' (1964) backscattering law, found adequate from previous experimentation. The fit involved adjustment of three parameters: slope parameter C , radar cross-section σ , and delay to the subradar point.

* The time-delay "residuals" (or difference between observed and theoretically predicted Earth-Mars displays) are easily converted into altitudes by multiplying by $-1/2$ the velocity of light or by -0.15 km per μsec .

Reduction of the entire set of delay residual data for 1967 and 1969 produced the relative altitude-versus-longitude plots for four separate 3° - 4° wide north equatorial latitude belts, centered on 3° , 7° , 11° , and 22° N, as shown in Fig. 11. The spatial resolution for each plotted point on the surface is about 5° in longitude or latitude, or 300 km. The error bars are considered conservative estimates; the measurement repeatability was found to be within 200 meters rms.

There is a striking similarity between the four topographic profiles. The topographic variation in the north equatorial belt, although large in magnitude, changes only slowly, contrary to the variation in radar reflectivity. The profile at 22° N differs from the 11° and 7° N profiles, mainly because of the broad ($\sim 30^{\circ}$ wide), high (~ 5 km) Elysium bright area. This tends to confirm the statements often made by Capen (1966) and Binder (1969), that Elysium is a high plateau. Near 40° longitude, the Chryse-Xanthe desert is a broad depression extending northward and apparently including part of Niliacus Lacus, a dark patch just south of Mare Acidalium. At 285° W longitude, the dark area Syrtis Major exhibits a rather abrupt increase in elevation (~ 5 km) over about ten degrees toward the westward bordering bright area, Aeria. The 7° N profile shows a minor peak at 250° longitude, in the Aethiopis desert. This peak does not appear in the other profiles. Contrary to Binder's (1969) conjecture, no indication of depressions were detected for the Phison and Euphrates canals located in the Arabia desert, near 330° longitude.

The profiles do show narrower structure, but because of the 5° spatial resolution and measurement accuracy, it is doubtful that they actually represent local variations in elevation.

The highest region found in all three profiles was in Tharsis, at about 100° longitude. The maximum elevation difference obtained was ~ 12 km.

During the 1969 opposition, the JPL team of Goldstein et al. (1970) used phase-coded 12.5-cm CW radar for delay studies of Martian topography. They looked at five different range gates simultaneously, each gate spaced 750 m apart in range. The output of each range gate was sampled every $1/640$ second, the autocorrelation function calculated by a computer, and then Fourier-transformed to yield power spectra, 640-Hz wide (and resolution of 10 Hz), which finally were averaged over the 9 minutes round-trip flight time (integration time), and displayed on an x-y plotter. This real-time display permitted observers to follow the large changes in topography (some 12-km variation, which is several times greater than the 4.5-km "field of view" of the set of five range gates), by properly adjusting the delay. The computer could only handle five range gates simultaneously. The 640-Hz width is the largest "effective" Doppler spread in the subradar region, while the limb-to-limb bandwidth is 7600 Hz, at $\lambda 12.5$ cm. The range (to the subradar point or center of each range zone) was estimated by using cross-correlation techniques and comparing each power spectrum obtained with a set of (30) theoretical power spectra, computed for a planet of the same radius, apparent rotation rate, and with a surface roughness assumed to give a similar exponential scattering law at very small angles ($\phi < 2^{\circ}$). The limited range resolution (0.3 km) and Doppler resolution (10 Hz) was also compensated for in this computation. The best fit gave the best estimate of range.

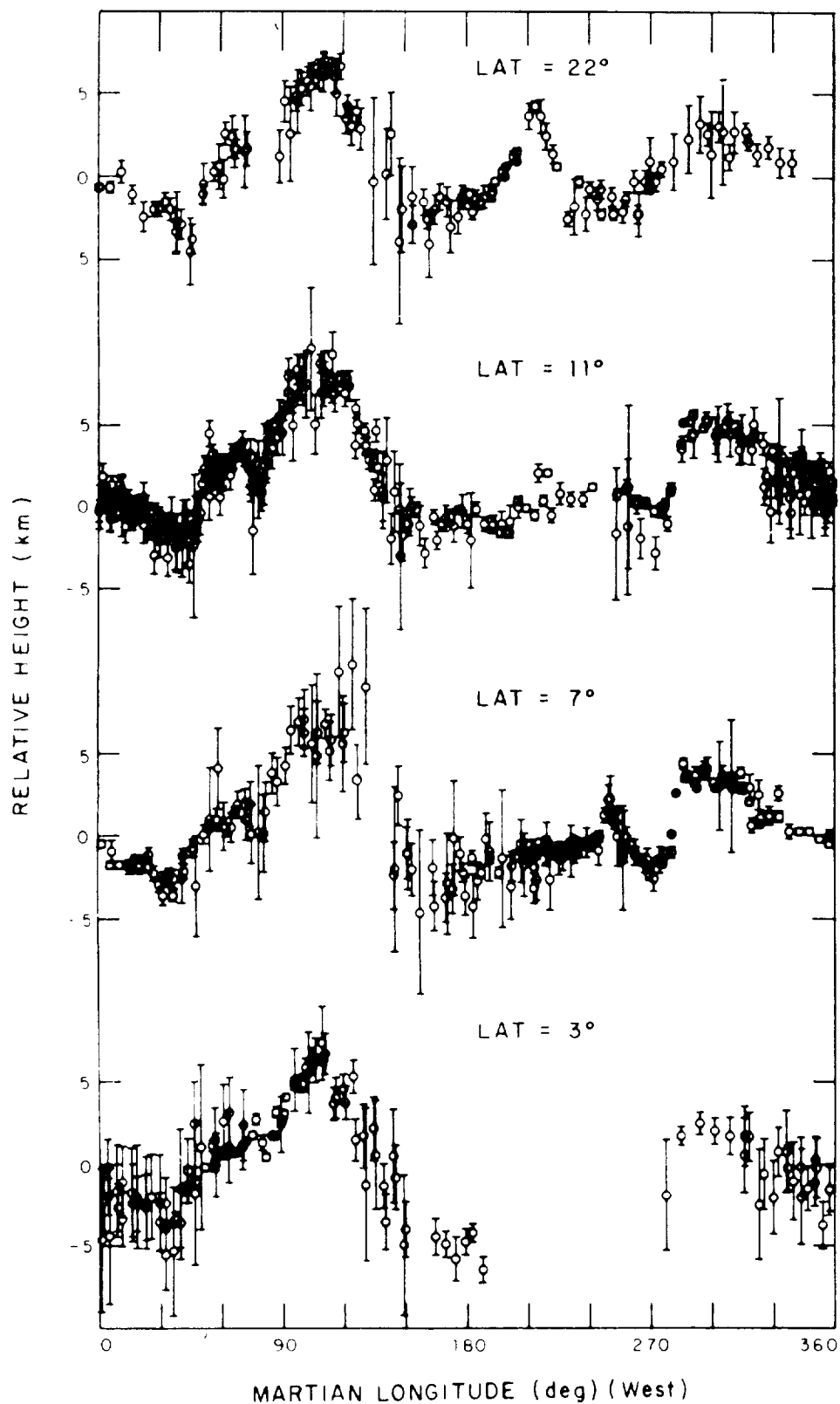


Fig. 11. Topography variation with longitude in four latitude steps from 3° to 22°N (Lincoln Laboratory, 1970).

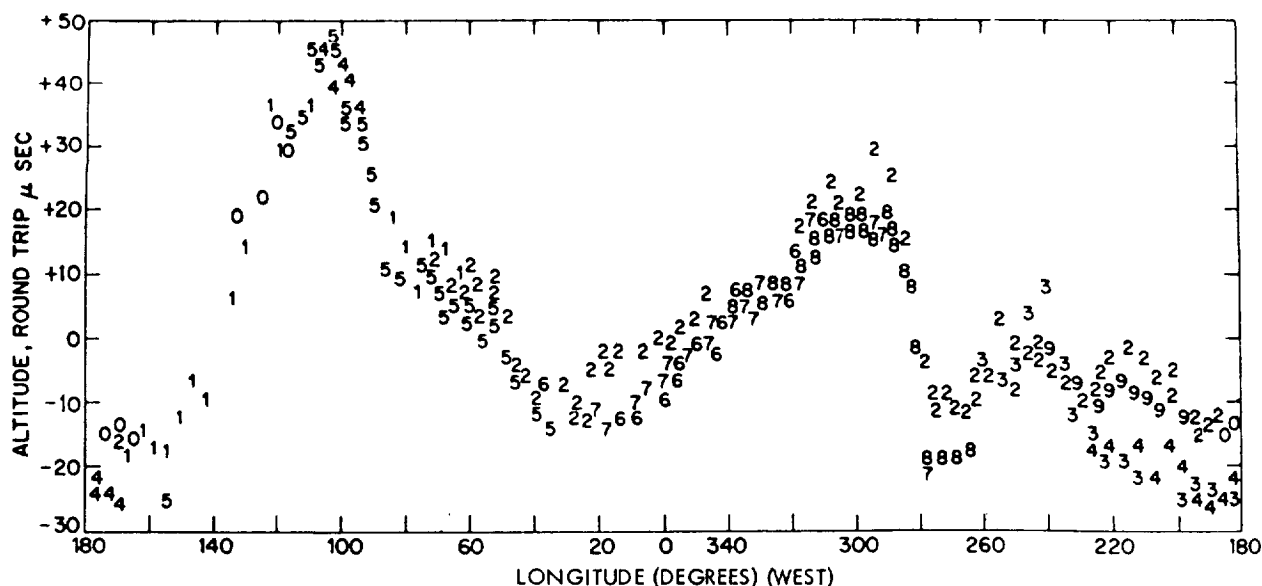
The JPL results (Goldstein et al., 1970) of relative altitude-versus-longitude were given in one plot (see Fig. 12), with subradar data points varying in latitude from 3° to 12°N. Each point represents an average measurement over a rectangular area ~90 km wide in a N-S direction by ~220 km in the E-W direction. They are very similar to the MIT results given in previous paragraphs. Tharsis was found to have the highest elevation, with Aeria next highest, and neighboring Syrtis Major dropping by 4 km "nearly linearly across its full width from Aeria to Moeris Lacus" (its eastward border). Mare Cimmerium's northern tip (~3° latitude) is lower. The lowest region found was in the large Amazonis desert, just west of Tharsis. The maximum elevation difference obtained was ~11 km.

3.3.5 TOPOGRAPHY — CROSS-SECTION — ROUGHNESS CORRELATION

The MIT (Lincoln Laboratory, 1970) results of 1967 and 1969 on topography, cross-section, and roughness were compared with de Vaucouleurs' (1967) luminance results from his photometric map, which averaged 1941 and 1958 data, in an attempt to establish any possible correlation. The mathematical techniques of correlation (cross-correlation functions) were systematically applied to these data by the MIT group (see Pettengill et al., 1969).

The results of the correlation analysis were as follows:

- 1) Topography is not correlated with cross-section or luminance, and is probably not correlated with roughness.
- 2) Cross-section is anticorrelated with both luminance and roughness.



Note: The digits refer to latitudes according to the code:
3=3°N, 4=4°N, ... 0=10°N, 1=11°N, and 2=12°N.

Fig. 12. Topography variation with longitude in latitudes 3°-12°N (Goldstein et al., 1970).

- 3) High cross-sections and low luminances (visually dark areas) tend to be associated with west-rising slopes. This conclusion, however, may be influenced by the fact that the only large cross-section regions mapped, Syrtis Major and Trivium Charontis, are both west-rising slopes.

These results apparently support the view that dark areas produce a strong quasi-specular echo, and suggest that high cross-section regions are, on the whole, smoother than their surroundings. Also, results indicate that dark areas tend to lie on the eastern slopes of highlands, which is consistent with the wind-blown model defining dark areas as bare rock (exhibiting strong radar reflectivity), and the bright areas as dust-covered surfaces (exhibiting low radar reflectivity).

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APPENDIX

MARS RADAR OBSERVATIONS IN 1971: TOPOGRAPHY AND
RADAR CROSS-SECTIONS

During the very favorable opposition of 1971, two groups of investigators, at MIT and at JPL, using the same techniques, have made extensive measurements of Martian topography and radar cross-sections in the Southern Hemisphere (equatorial belt 14° to 18° S), utilizing improved radar and computer processing capabilities. Both groups were able to resolve some of the larger craters, and also some steep scarps, crater rims, etc. Observations were begun in June 1971, and were continuing into November, as of this writing. Only preliminary results of their work are available and are presented here.

MIT Observations (Pettengill et al., 1971)

The MIT group at Haystack operated at 3.8 cm, transmitting phase-coded CW. Lateral surface resolution was 1.3° in latitude and 0.8° in longitude. Range resolution was of 0.90 km. Repeatability reached 75 meters at best when reflectivity was high. Results given concerned the topography mainly. Figs. A-1(a), (b), and (c) show the altitude variations around Mars at latitudes from 14.5° to 16.8° S. They are very similar to those obtained by Goldstein and co-workers (in 1971). Many craters also were resolved, as well as rims and scarps. In particular, there is a sudden drop of 4.5 km in Pyrrhae Regio near 45° W (lowest depth encountered). Then, an extremely radar bright area (high radar cross-section) near 15° W in Deucalionis Regio. Three abrupt transitions (A, B, C) near 345° W obviously correspond to craters (one B with depth 1 km). Between 310° and 275° W in Iapygia they noted an apparently very large (2000 km) basin some 2 km deep, with another nearly concentric crater 500 km across and 0.5 km deep. There is a nearly level plain from 258° to 243° W with a few small craters. At 230° W, a large crater 340 km across, 1 km deep (D) with a well developed lip is noted. It corresponds to a crater seen in a Mariner 1969 FE photograph. From 198° to 183° W there is a large depression (E and F) with a very irregular bottom, in Zephyria. At 167° W, a small, 2 km deep feature (G) was obtained in Titanum Sinus. At 149° W, there is a crater (H). Then, the remarkable "twin peaks" at 122° and 100° W in Phoenicis Lacus, the latter displaying extremely high radar brightness (strongest at 108° W). These features seem to continue in the South Hemisphere from those seen in the North Hemisphere, and, may thus form a double ridge of major importance. Between 125° and 121° W no echoes could be obtained. Either the region is exceedingly rough (at wavelength scale) or of exceedingly low radar reflectivity or both. From 98° to 80° W there is a very regular downslope from the peak with strong reflectivity, which is apparently free of craters.

One surprising general result was the lack of correlation between areas of high radar reflectivity and visually dark features (as found in the north equatorial belt).

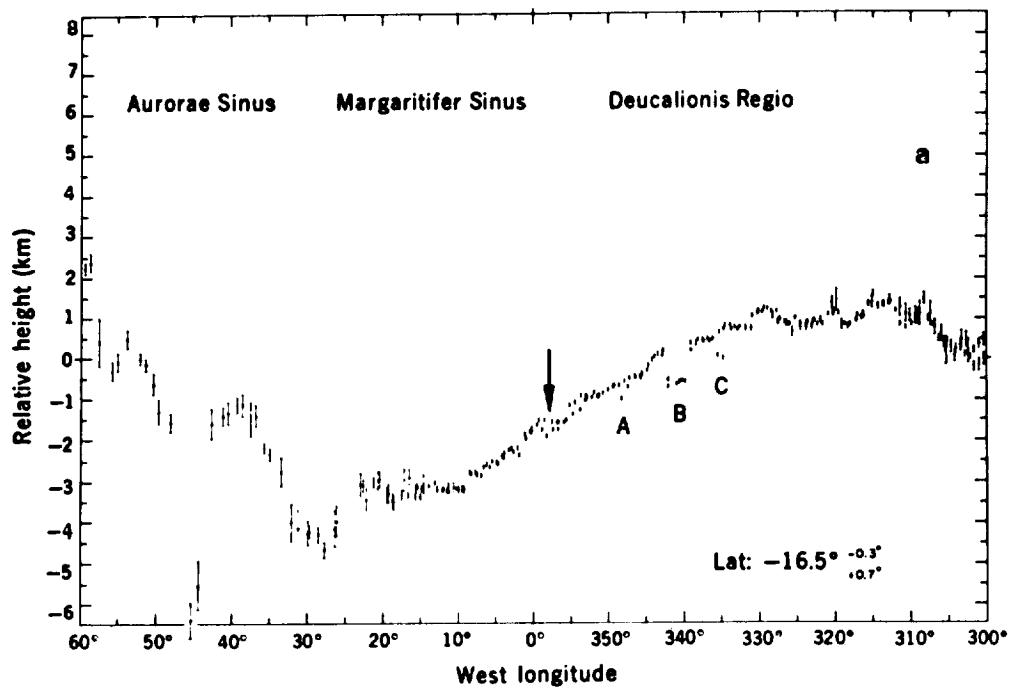


Fig. A-1(a). Topography variation with longitude near 16.5°S latitude (Pettengill et al., 1971) - (MIT at $\lambda 3.8$ cm).

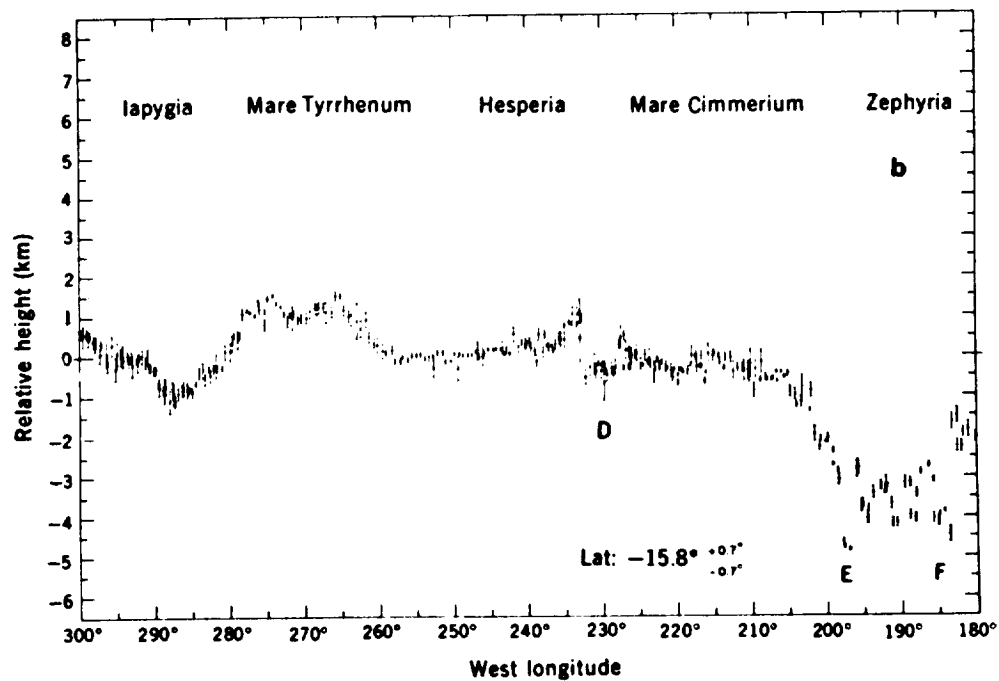


Fig. A-1(b). Topography variation with longitude near 16°S latitude (Pettengill et al., 1971) - (MIT at $\lambda 3.8$ cm).

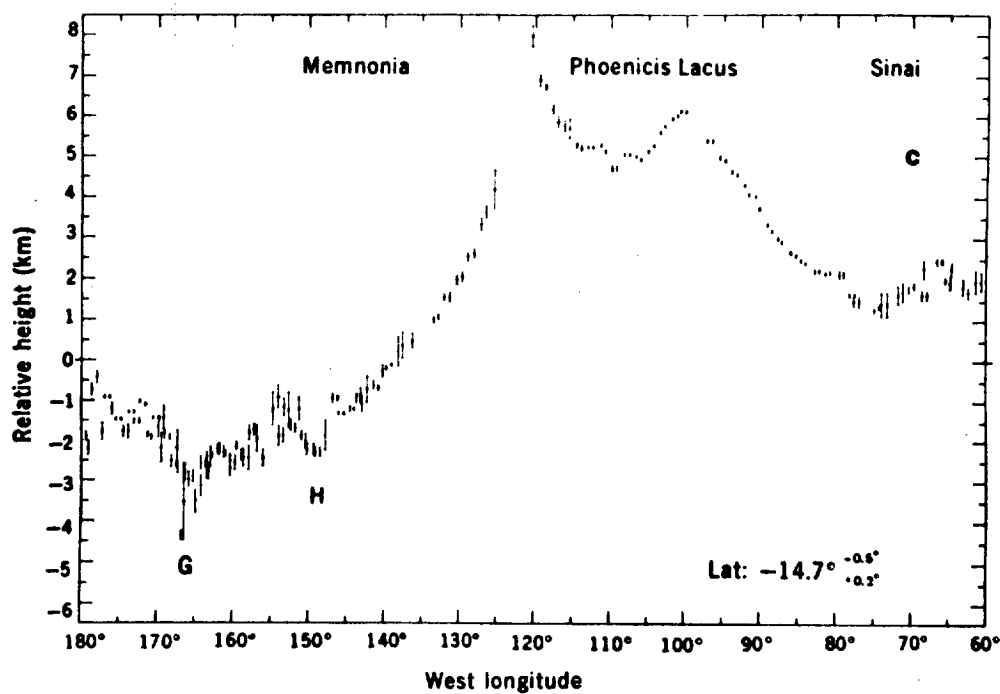


Fig. A-1(c). Topography variation with longitude near 15°S latitude
(Pettengill et al., 1971) - (MIT at $\lambda 3.8$ cm).

JPL Observations (Downs et al., 1971)

The JPL group at Goldstone operated at 12.5 cm with a 300 kW transmitter and a 20°K system temperature. Using delay-Doppler mapping on the subradar region, they recorded every 30 seconds (integration time) an array of 32 delay (rings) by 64 Doppler (strips) resolution cells. The delay rings gave a resolution of 0.45 km in range, while the Doppler strip resolution was 9.4 km. The lateral surface resolution was ~100 km, corresponding to a front-cap diameter ~1.6°. Repeatability of altitudes obtained reached 40 meters, whenever the points were very close and the echo strong.

Results were of two sorts:

- 1) Topography. Large craters and small craters were resolved with occasional resolution of their rims. Figure 2(a) shows the altitude profile obtained around Mars at latitudes from 13.8° to 14.6°S. It is similar to that obtained in northern equatorial belts. There is a difference in altitude of some 13 km between lowest (120°W) and highest points (85°W). Slopes are of the order of 1°. The fine structure is due to craters with some large craters (at 230° and 188°W) identifiable on Mariner 1969 FE pictures.
- 2) Radar cross-section. Wide fluctuations are noted as before, due either to variations in dielectric constant and/or surface roughness. Crater floors are bright but their crater walls are not. Figure 2(b) shows the fractional radar cross-section around Mars at the same latitudes as Fig. 2(a).

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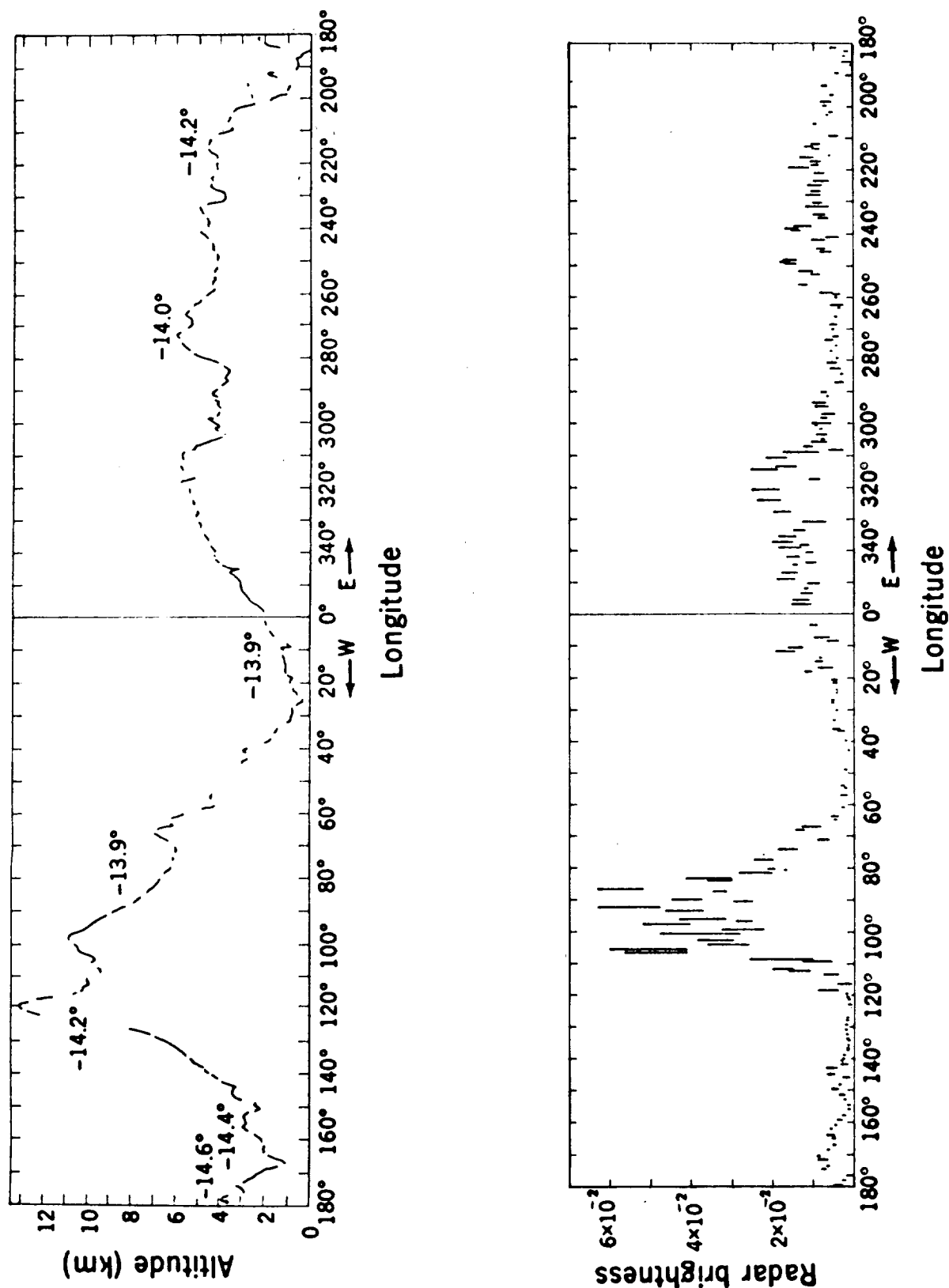


Fig. A-2. Topography and radar cross-section variation with longitude near 14°S latitude (Downs et al., 1971) - (JPL at $\lambda 12.5$ cm).

3.4 CHEMICAL AND PHYSICAL PROPERTIES

INTRODUCTION

So far, very little is known about the chemical, physical, mineralogical or petrological nature of the Martian surface. The observational information available to date has been gained solely by means of remote-sensing methods: spectrophotometry from UV to IR (and filter colorimetry), polarimetry (mostly in the visible), infrared and microwave radiometry, and radar probing. Of these methods used from Earth, only UV and IR spectrometry, filter colorimetry (in the visible), and infrared radiometry have been implemented on board spacecraft (Mariners 6 and 7), and used in conjunction with the television imagery.

Beyond the limited observational information which provides some guidelines, present "knowledge" is speculative. Speculations about the nature of the Martian surface are based on limited knowledge and linked to speculations about types of geological processes which are and have been operative for some time at or near the surface. Thus, considerable uncertainty prevails and probably will continue to prevail until landers return more exact and detailed information from the surface itself.

Presented here is the factual and interpreted information obtained from remote-sensing and also some speculations derived from them.

This section contains two separate portions: one dealing with the physical and chemical properties of the actual ground or soil, the other with the chemical properties of the polar cap deposit.

PHYSICAL PROPERTIES OF THE GROUND SURFACE MATERIAL

The top layer of Martian surface material in bright and dark areas is expected to be granular, much of it fine-grained and not particularly cohesive. Atmospheric gases (CO_2 , CO , H_2O) must be adsorbed in this porous soil, which appears to be stirred at least sometimes during the Martian year.

Large eroded blocks of rocks (boulders) are also expected near the older craters, but partly or completely buried in the fine material and the impact rubble which no doubt forms most of the epilith (regolith) of Mars. Smaller angular blocks are probably present also, near the more recent small craters. The Mariners did not have sufficient resolution to provide direct photographic information on the small-scale appearance of the epilith. In any case, erosion has been much more active than on the Moon, as can be seen by comparing the Martian and lunar craters (see Section 3.6, Photographic Atlas), and the fine material has been distributed widely over the whole planet, mostly by aeolian transport and deposition.

The bearing strength of the granular dry Martian "soil" is probably lower than that of lunar soil, which is on the order of $2 - 5 \times 10^5$ dynes cm^{-2} . Cohesion at the top is lower because there is no high vacuum nor particle sintering effects; at little depth, it must rapidly increase from packing and

perhaps some humidity. Bearing strength varies with grain size distribution as well as mean grain size and packing, all of which are surely governed by the aeolian transport and deposition processes. It is thought that one of the important differences between bright and dark areas lies in the mean grain sizes. See subsection on Granularity, where other physical properties, such as density and dielectric constant estimates are also given. Table 1 summarizes the best estimates of the most important physical parameters of the Martian top material.

Table 1. Estimates of average physical properties of Martian surface material

		Bright Areas	Dark Areas
A*	-Bolometric Albedo (assumed) (dimensionless)	0.25	0.15
γ^{-1}	-Thermal Inertia $\left[\gamma^{-1} = (K\rho C)^{1/2}\right]$ (cal cm ⁻² sec ^{-1/2} deg ⁻¹)	0.004	0.006
ρ	-Density (g cm ⁻³)	(1.2)	(2)
C	-Specific Heat Capacity (assumed) (cal g ⁻¹ deg ⁻¹)	0.15	0.15
K	-Thermal Conductivity (cal cm ⁻¹ sec ⁻¹ deg ⁻¹)	5.10 ⁻⁵	12.10 ⁻⁵
ϵ/ϵ_0	Dielectric Constant (dimensionless)	(2.5)	(3.5)
d	Mean Particle Diameter (microns)	50	200

Granularity

The bright areas of Mars are most probably constituted of fine, granular material of high porosity. Many lines of evidence converge to support this statement. First, the visual observations of yellow clouds indicate they almost always arise over bright areas; second, the colorimetric observations of both these clouds and bright areas are similar; third, the polarimetric observations show a negative branch at small phase angles; fourth, the spectrophotometric observations of both the yellow clouds and bright areas are similar, with a characteristic decline in albedo (reflectivity) from the red to the blue; fifth, the analyses of yellow cloud fallout times are in accord with expected particle sizes; sixth, the infrared radiometric observations of bright areas yield thermal inertias characteristic of granular, porous material; and finally, the radar observations show low dielectric constants for bright areas, indicative of pulverized material to a depth of at least a meter. To this series of evidence

secured from Earth, may be added the ones returned by the Mariner 6 and 7 spacecraft, which have been discussed under the heading Dark and Light Areas in Section 3.5 on Morphology and Processes.

The Earth-based observations agree rather well in consistently indicating a mean particle diameter of about $50\ \mu$ for the bright areas, which means fine dust is covering them. Such dust is certainly capable of being transported by winds (to produce the patterns over crater floors in the Meridiani Sinus region, as revealed by Mariners 6 and 7), and even, provided winds are strong enough, of being lifted up to form yellow clouds, as Ryan (1969) concluded from a study of the dynamics of dust-devils, or Sagan et al. (1971) from Martian wind regimes.

For the dark areas, the evidence of granularity is less certain. Photometry, polarimetry, and infrared radiometry indicate somewhat larger grains--about $200\ \mu$ in average--for the dark areas. On the other hand, radar shows higher dielectric constants, which independently suggest either compacted granular material or possibly solid rock, which, of course, could exist just below the granular layer.

Density

Tentative estimates of densities (and porosities) can be obtained from the radar observations, if one is willing to make many uncertain assumptions. Hence the speculative nature of such estimates. Indeed, there is a formula (Rayleigh's) which relates density to the dielectric constant of pulverized and nonpulverized material. If one assumes a powdery limonite layer for the bright areas, then the 'observed' dielectric constant can yield the density. Pollack and Sagan (1970) thus obtained a density of $1.2\ \text{g cm}^{-3}$ for Amazonis (using Goldstein [1965] radar observations giving a dielectric constant of 2.6). For the dark areas, they assumed compacted limonitic material (a questionable assumption), and from the higher dielectric constant (3.5-4.5) observed by radar over Syrtis Major, they derived a density of 1.5-2, which they considered probably a lower limit.

CHEMICAL PROPERTIES OF THE GROUND: GENERAL ASPECTS

The composition of the Martian surface may be quite different from that of the Earth (and perhaps more akin to that of the Moon), for two basic reasons: (1) the starting materials of this small, apparently incompletely differentiated planet (see Section 2 on Interior) may have been quite different from those of Earth, and (2) aqueous erosion (flowing water) and weathering have probably not been a dominant process (see Section 3.5 on Morphology and Processes) in the last few (perhaps four) billion years of Mars' history. On Earth, aqueous erosion and weathering have produced an immense variety of sedimentary rocks differing in type and composition, and often later these rocks have been transformed by metamorphism; i. e., action of pressure and temperature at depths. It is not too surprising, therefore, that recent evidence from our most informative remote-sensing method from Earth (spectrophotometry) indicates that the surface rocks or soil of Mars as a whole appear to be predominantly igneous, with iron-bearing basalt the fundamental type of rock. Very slow chemical weathering (possibly oxidation by traces of O_2 or O_3 catalyzed by minor H_2O available) has most likely stained their surfaces with ferric oxides of various degrees of hydration. This will be treated in detail under "Composition Inferred

From Reflectance Spectrophotometry." Other products of weathering, such as carbonates (whose formation may require catalysis by liquid H_2O), might be expected. From the IR spectra, however, carbonates seem very low in abundance (as none of the strong carbonate bands in the $1.7\text{-}2.5\ \mu$ region has been detected so far). Products of reaction with a perhaps N_2 -rich former atmosphere, namely nitrates, have likewise not been detected (but their spectral bands are very weak anyway).

There should be an abundance of products of asteroidal or meteoritic cratering and ablation (by the atmosphere): metals and oxides, glass spherules, shocked minerals, etc., besides the common meteoritic silicates in the probably thick rubble-and-dust epilith (regolith) layer of Mars.

If the crust has been geologically active with mild volcanism (outgassing, hydrothermal action, ...) then sublimates (e.g., sulfur) and hypogene minerals (e.g., sulfide ores) may occur in favored localities in the upper crust. If magmatic intrusions have taken place, contact metamorphic minerals would then also be present. If the crust has been active with tectonism, such as faulting, thrusting, ..., then one could expect cataclastic metamorphism locally; and, with large orogenic uplifts, regional dynamothermal metamorphism in the deeper parts of the crust. Of course, these possibilities are mere speculations.

Likewise, and even more speculative is the case: if, early in the history of the planet, there was once a wet age on Mars (ocean or dense watery atmosphere), then deep sedimentary layers should be present in parts of the crust, and because of later history (impacting, etc.), near surface rocks may show strong compositional variations. One might still find evaporite minerals (salts, such as Na, Mg chlorides, sulfates, ...) in remnants of ancient marine beds.

3.4.1 Composition Inferred From Reflectance Spectrophotometry

So far, the only remote-sensing method effective in providing definite clues to the composition of the Martian surface has been reflectance spectrophotometry. The reflectance spectra of rocks and minerals in the 0.2 to $2.6\ \mu$ range exhibit two types of absorption band: (1) broad bands resulting from electronic transitions, and (2) narrow bands due to vibrational modes.

An example of the first type is the ferrous Fe^{++} ion band, occurring at about $1\ \mu$ (0.9 to $1.1\ \mu$) in the mafic silicates, while examples of the second type are the 1.4 and $1.9\ \mu$ sharp bands due to the hydroxyl OH^- stretching vibration, as occurring in quartz, feldspars, and other light-colored minerals, and in some hydrous minerals. Such bands in a reflectance spectrum, either individually or in combination, can be used to identify minerals or to narrow down their possible choices. The position of the band also depends on the crystal field symmetry.

In recent years, the reflectance spectra of many rocks and minerals have been obtained; for example, by Hovis and Callahan, 1966; Adams and Felice, 1967; Hunt and Salisbury, 1970; Greenman et al., 1967; Adams, 1968; and Ross et al., 1969. Some of the results, other than those mentioned above, are given in the listing that follows (see Adams, 1968).

- 1) Most of the common iron-bearing silicates (olivines, orthopyroxenes, clinopyroxenes) have characteristic spectra, with a major band between 0.9 and 1.1 μ due to Fe^{++} (usually in sixfold coordination, and another band between 1.8 and 1.9 μ due to Fe^{++} , residing "probably in a highly disordered octahedral site" (Bancroft and Burns, 1967; White and Keester, 1967).
- 2) Ferrous oxides (magnetite, ilmenite) are opaque and show no structure.
- 3) Ferric oxides (hematite, goethite, limonite*) exhibit an absorption band at 0.85 to 0.89 μ due to ferric ion Fe^{+++} in sixfold coordination. Goethite and limonite have no OH^- band.
- 4) Iron-bearing carbonates have both a broad band near 1 μ and narrow bands between 1.7 and 2.6 μ , which are quite characteristic.

Mixing of different minerals in a rock tends to average the spectra; for example, a basalt combining orthopyroxene (0.9 μ band) and olivine (1.02-1.05 μ band) would show a band only at 0.95 μ . Lack of structure is ambiguous and may be due to very small particle size (<10 μ) or glass (as found in lunar samples). The particle size effect, however, may act the other way (i.e., small size may enhance structure), depending on the opacity or transparency of the mineral. (See Salisbury and Hunt; 1968, 1969.) Thus, the identification or narrowing down of possibilities is often a difficult, if not impossible, matter. It is also complicated by the presence in actual reflectance spectra of additional bands due to Mars atmospheric constituents, such as CO_2 and H_2O , as well as similar (telluric) bands due to the Earth's atmosphere, which may overlap or block out the characteristic bands of the minerals to be identified. Fortunately, these atmospheric bands are well known for both Mars and Earth (see Section 5.1).

3.4.2 Reflectance Spectra of the Bright and Dark Areas (Earth-based results)**

The spectral reflectivity curves or the spectral geometric albedo curves for Martian bright areas and dark areas in general are now well established, with an accuracy of a few percent, in the 0.3 to 1.1 μ spectral region. Refer to the review articles by McCord and Adams (1969), and especially to McCord et al. (1971), which gives the most recent results. These results were obtained at the time of the 1969 opposition by McCord and Westphal (1971), at Cerro Tololo Inter-American Observatory (Chile), by means of a narrow-band spectrophotometer using 52 interference filters spanning from 0.3 to 2.5 μ . Figure 1 summarizes the best available data for dark and bright areas. Figure 5 of Section 3.2 represents the McCord and Westphal (1971) curves (0.3 - 1.1 μ) for seven areas. Seasonal changes in dark areas were also investigated in the 0.3-1.1 μ region, by McCord and Adams (1969) for Syrtis Major (see Fig. 2).

*Limonite is a mixture of hematite, goethite, water of hydration and many impurities.

**Regretfully, no Mariner 1969 IRS final results on the soil composition of the scanned Martian surface have been available (January 1972). The presence of silicates has however been repeatedly mentioned by Pimentel and Herr.

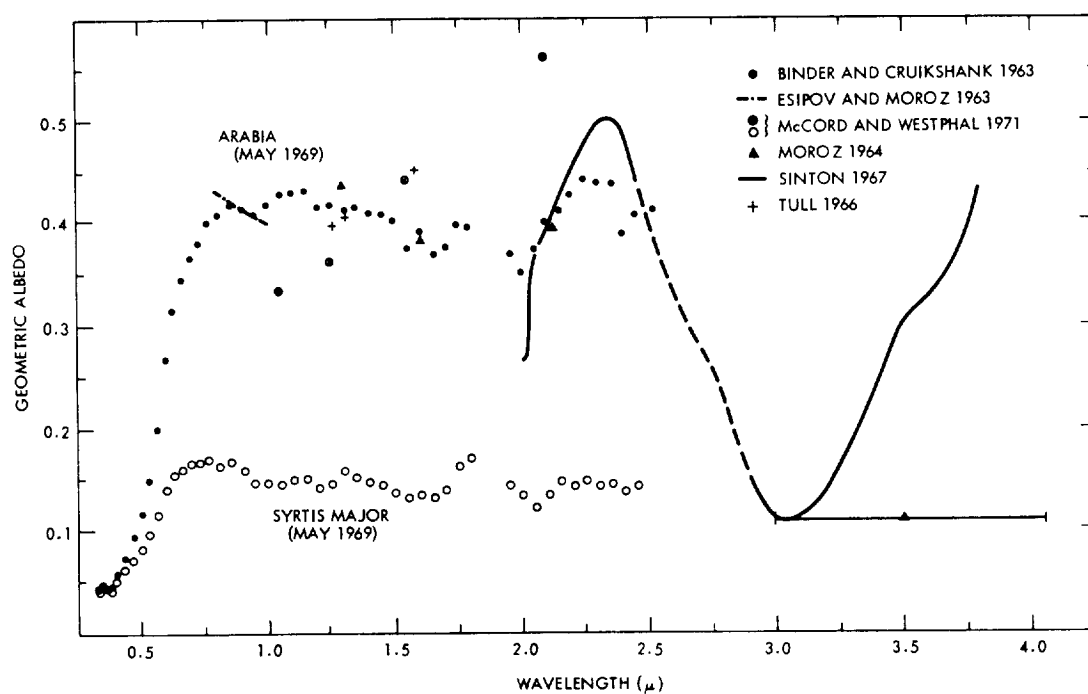


Fig. 1. Spectral geometric albedos of a typical bright area (Arabia) and dark area (Syrtis Major) for the 0.3 to 2.5 μ spectral region according to the data of McCord and Westphal (1971) and other investigators. McCord et al. (1971)

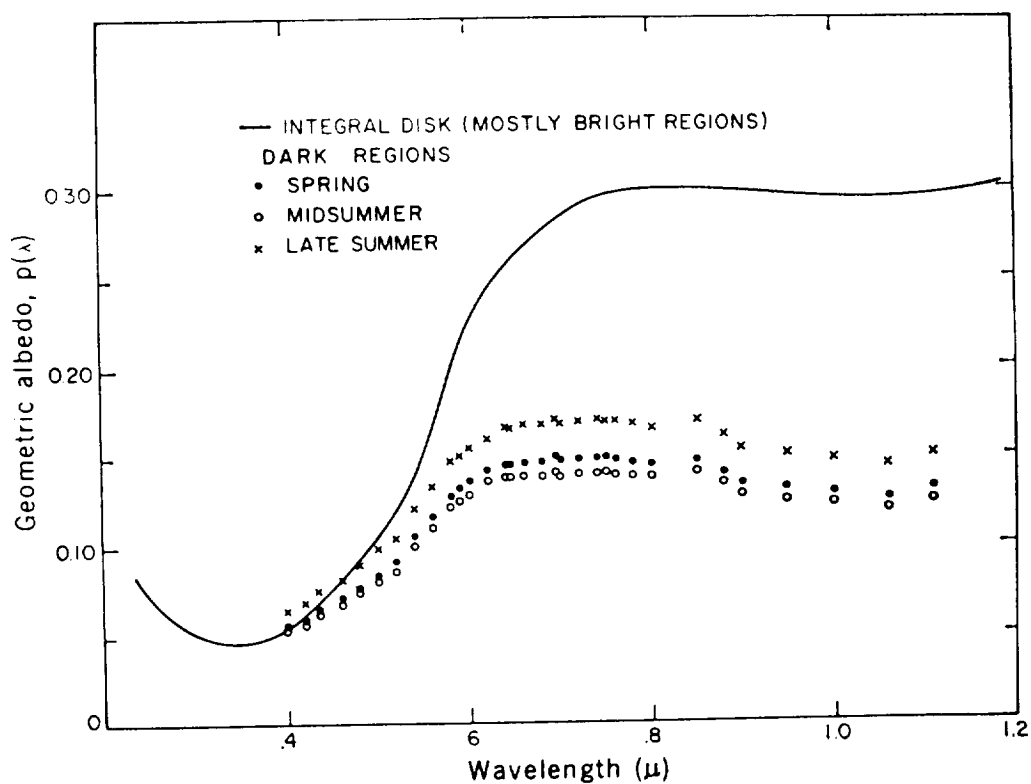


Fig. 2. Seasonal changes in dark areas (McCord and Adams, 1969).

The characteristic absorption features and slopes seen in the 0.3 to 1.1 μ curves are amenable to interpretation.

The extension of these curves beyond 1.1 μ and up to almost 4 μ has been attempted by various investigators as seen in Fig. 1, but the results are not in good agreement. Recently, however, the portion up to 2.5 μ seems to have been established with fair reliability and accuracy by the work of McCord and Westphal (1971) mentioned above. The authors caution that the data points in this extended region show more scatter, implying that the newly revealed absorption features need confirmation before proper interpretation can be carried out. The full interpretation of the 0.3 to 2.5 μ reflection spectrum or spectra already promises improved deciphering of the composition and mineralogy of the surface materials.

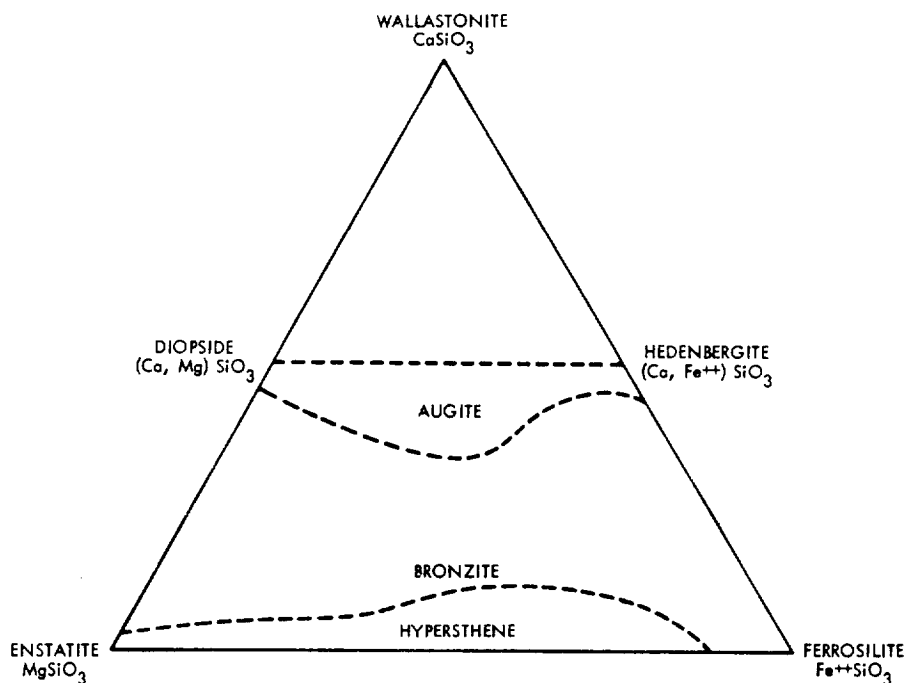
From 2.5 to about 4 μ , the continuation has been very much more uncertain, being based only on the older measurements from Moroz (1964) and Sinton's results (1967), which were marred by calibration difficulties; very recently, however, Beer et al. (1971) published their very high resolution 2.5-3.2 μ spectrum. This region also may reveal some most interesting absorption features. However, there is insufficient laboratory data on rocks and minerals in the mid-infrared region to afford safe interpretation of the observed Martian spectral features. Beyond 4 μ , thermal emission of the planet starts to take over, predominating increasingly over reflection.

Description and Interpretation of the Martian Spectra (see Figs. 1 and 3)

The reflection curves of bright and dark areas of Mars show an overall similarity, with the same steep slope rising from 0.4 to 0.7 μ , indicating generally a very reddish material indeed; Syrtis Major and other dark areas are not green or grey, as sometimes previously reported, but reddish spectrally.* Arabia and other bright areas are higher in albedo and redder than dark areas.** Although the reflection curves of light and dark areas are similar, they differ in their near infrared absorption features, as well as described below. The differences are significant enough to indicate a probable "different mineralogical composition, and not simply a particle size difference," to quote McCord and Westphal, 1971, whose curves serve as a basis for the interpretations given below.

*"Color" here means relative spectral color and refers specifically to the spectral flux distribution, and not to the customary physiological sensation of color (to human eyes).

**The stability of their relative color, which earlier conclusions asserted (McCord and Adams, 1969), now seems questionable: relative to Syrtis Major, which remained constant, Arabia was found to be significantly redder and brighter in March than in May 1969 (McCord and Westphal, 1971). This unexpected observation is in conflict with that of the traditional wave of darkening and remains to be explained. However, more data at different seasons and planetary phase angles are needed to define these effects.



There are two main series of pyroxenes:

- 1) Calcium-rich pyroxenes, or clinopyroxene series (because they are all monoclinic), with end members: diopside and hedenbergite. The intermediate members are grouped under the name augite.
- 2) Calcium-poor pyroxenes, or orthopyroxene series (mainly orthorhombic), with end members: enstatite and ferrosilite. Intermediate members are bronzite and hypersthene. The orthopyroxenes are less abundant terrestrially than the clinopyroxenes.

Fig. 3. Ternary diagram $(\text{Ca}, \text{Mg}, \text{Fe}^{++}) \text{SiO}_3$ showing the compositional variations of pyroxenes.

The 0.3 to 1.1 μ portion of the curves exhibit the following features:

- 1) A strong absorption in the blue-UV (0.3-0.4 μ) which is stronger for the bright areas. This usually characterizes ferric oxides -- if only common geological materials are considered. The bright areas would then be enriched in ferric Fe^{+++} oxides.
- 2) A possible band at ~ 0.85 -0.87 μ , only in bright areas. Its intensity is very weak: 2 to 3 percent at most according to Sinton (1967) while Younkin (1966, 1969) claims it is not present at all. There appears to be a suggestion of it in the curve for Moab. Such a band is due to the ferric Fe^{+++} ion and appears in the spectrum of limonite (Sagan et al., 1965; Draper et al., 1964); however this band is not unique to limonite, although it is commonly referred to as the "limonite band." If this band truly were present in the bright areas spectra, the statement of Fe^{+++} enrichment in such areas would be reinforced.
- 3) A weak absorption feature at 0.80-0.85 μ in the Syrtis Major curve, even weaker in the Arabia curve. This feature is difficult to distinguish from feature 2), because data here obtained with one filter is not well resolved. No specific interpretation is given, although it appears to belong to the darker colored ferromagnesian silicate minerals, such as augite (clinopyroxenes). See band location in Adams (1968). Interestingly, McCord and Westphal mention that this absorption feature becomes stronger as the dark area becomes darker.
- 4) A narrow absorption feature between 0.9 and 1.0 μ , centered at 0.95 μ for the Arabia, Moab, Neith Regio bright area curves only. This feature appears compatible with the presence of the lighter-colored ferromagnesian silicate minerals, such as hypersthene and/or bronzite (orthopyroxenes). * In fact, McCord and Westphal note that this feature becomes less strong as the albedo decreases.

This narrow feature was unreported previously because spectral resolution was insufficient and because older data usually pertained to an average of many bright areas.

- 5) A broad absorption depression from 0.90 to 1.1-1.2 μ present only in the dark area curves, namely for Syrtis Major, Mare Acidalium, Iapygia, and Meridiani Sinus. This important feature is characteristic of ferrous Fe^{++} ion in sixfold coordination. (The exact position of the band depends on the crystal structure.) It is probably originating here in a ferromagnesian silicate mineral (since typically Fe^{++} resides in them), perhaps olivine and clinopyroxene or a mixture (as these dark minerals often occur together). McCord and Westphal mention that the broad feature becomes stronger as the dark area becomes darker.

*Confirmation of such an identification would be provided by a second band at ~ 1.8 μ (see Adams, 1968). The spectrum of McCord and Westphal (1971) unfortunately has a gap between 1.8-1.95 μ (telluric water vapor variations being responsible).

Earlier, McCord and Adams (1969) actually reported that this broad feature is stronger in dark areas, probably not distinguishing it from the then unknown narrow feature at $0.95\ \mu$ in bright areas, which they apparently saw as a weak absorption at about $1.0\ \mu$.

From the above analysis, one may conclude that although bright and dark areas are basically constituted by similar rock-forming minerals, namely ferromagnesian silicates, they differ in that bright areas are richer in orthopyroxenes, hypersthene for example, and ferric oxides, while dark areas are richer in clinopyroxenes and olivine, augite for example. These interpretations are, of course, only possibilities. Confirmation or rejection should be provided when the presence or absence of other characteristic features in the spectrum beyond $1.1\ \mu$ is more firmly established.

In the 1.1 to $2.5\ \mu$ portion of the spectra, not yet firmly established, ^{*}certainly several absorption features exist. We shall mention only (1) a general depression between about 1.3 and $1.7\ \mu$ for Syrtis Major and (2) a general depression between about 1.3 and $2.2\ \mu$ for Arabia. Both curves show a positive feature at about $1.8\ \mu$ greater in Syrtis Major. The sharp depression at $2.0\ \mu$ in both curves is caused by the atmospheric CO_2 absorption. No interpretations have yet been offered for the features of this spectral region.

Water of Hydration

Undoubtedly from the above, water of hydration is present in the Martian soil or rock minerals. Additional evidence has been reported such as the following: Sinton (1967), with his birefringent interferometer, obtained $2\text{--}4\ \mu$ spectra of Mars (see Fig. 1) which showed a very strong broad band at about $3\ \mu$, the shape of which followed that of a prominent H_2O band. For bright areas, the minimum was at $3.0\ \mu$, and for dark areas $3.1\ \mu$. Later, this general observation was confirmed by the high-resolution $2.4\text{--}4\ \mu$ spectra of Mars (integrated light) taken with a Connes' type interferometer (Beer et al., 1971). The best interpretation given is that this broad band is probably due to water of hydration or crystallization of hydrated minerals at the surface of the planet. The amount of this chemically bound water could not be estimated.

The shift from $3.0\ \mu$ to $3.1\ \mu$ noted by Sinton (1967) "may indicate compositional differences for the hydrated minerals" of the bright versus dark areas.

Laboratory Simulation Experiments

Laboratory spectral reflectivity curves from 0.3 to $1.1\ \mu$ for the Martian bright and dark areas were modeled by Adams and McCord (1969), using only geochemically expectable materials. They achieved a close fit only with an oxidized basalt.* Starting with the same fundamental basalt material, they

*Specifically, a fresh, dense olivine basalt from Little Lake, California, was attacked by dilute nitric acid, which dissolved and oxidized only the magnetite grains; upon drying, the solution precipitated a rust-colored stain on the unattacked mineral grains of the basalt. This stain was identified as limonite.

achieved a reasonable fit for both area types (see Fig. 4). The only difference was that bright areas required the more oxidized and finer grained material ($<50 \mu$ mean particle size). It was inferred that both area types were constituted of fundamentally ferromagnesian silicate rock material.

To simulate the seasonal darkening of Syrtis Major, variations of the oxidation state and/or mean particle size were not adequate. Only two darkening mechanisms were found to be satisfactory: (1) partial covering of the surface by a very dark grey or black material, possibly growth of grey vegetation or black microorganisms, the decay of which provides return to the original state; (2) addition of moisture to the surface, for example by condensation of atmospheric water vapor below 0°C . Drying restored the original aspect; therefore this mechanism was reversible.

Such modeling represents only a first-order attempt. Clearly much more work is needed. For example, the 0.95μ feature in bright areas was not matched. The limonite, or ferric oxides, coating or staining the silicate matrix are strong pigments, only a little of which is necessary to impart a reddish (orange or ochre) coloration to the Martian surface silicate particles. This limonite stain model, proposed several years ago by Van Tassel and Salisbury (1964), and Binder and Cruikshank (1965), is more plausible than the unrealistic but fashionable model of the fifties and early sixties. These unrealistic models proposed that powdered limonite or ferric oxides were the major surface constituent rather than silicates, as on Earth (Dollfus, 1957; Sharonov, 1961). Such outdated models were based on very meagre, strictly physical information derived from polarimetry and wide-band photometry/colorimetry.* These methods can give only particle size, albedo, and color, and cannot solve the compositional problem, as is possible via narrow-band spectrophotometry.

Exotic Interpretations

An ingenious compositional model of decidedly speculative caliber was proposed by Plummer and Carson (1969). It is based on the hypothetical carbon suboxide C_3O_2 , supposedly formed photochemically from atmospheric CO_2 and CO , according to the reaction: $\text{CO}_2 + 2\text{CO} \rightarrow \text{C}_3\text{O}_2 + \text{O}_2$. This compound readily polymerizes into heavier, rather hygroscopic molecules $(\text{C}_3\text{O}_2)_n$, which settle onto the surface. These molecules exhibit a range of color from pale yellow through orange, reddish brown, and violet, to nearly black, depending upon temperature and UV radiation. Plummer and Carson found the reflection spectrum of the dull yellow polymer to quite nicely match the reflection spectrum of Mars between 0.2 and 1.0μ . Therefore, they proposed the polymer as responsible for the colors of Mars, instead of the traditional limonite or ferric oxides. Major objections are that there is no certainty that such a polymer can be a stable geochemical material, under prolonged UV irradiation

*Cutts (1971) concluded from his broad-band colorimetric measurements (his "color-reflectivity" plots) on blue, green, and red pictures taken by Mariner 7 that "it may be possible to match the reflectivity characteristics of both light and dark areas with oxidized basalt, but if this is the case there must be a change in particle size as well as composition."

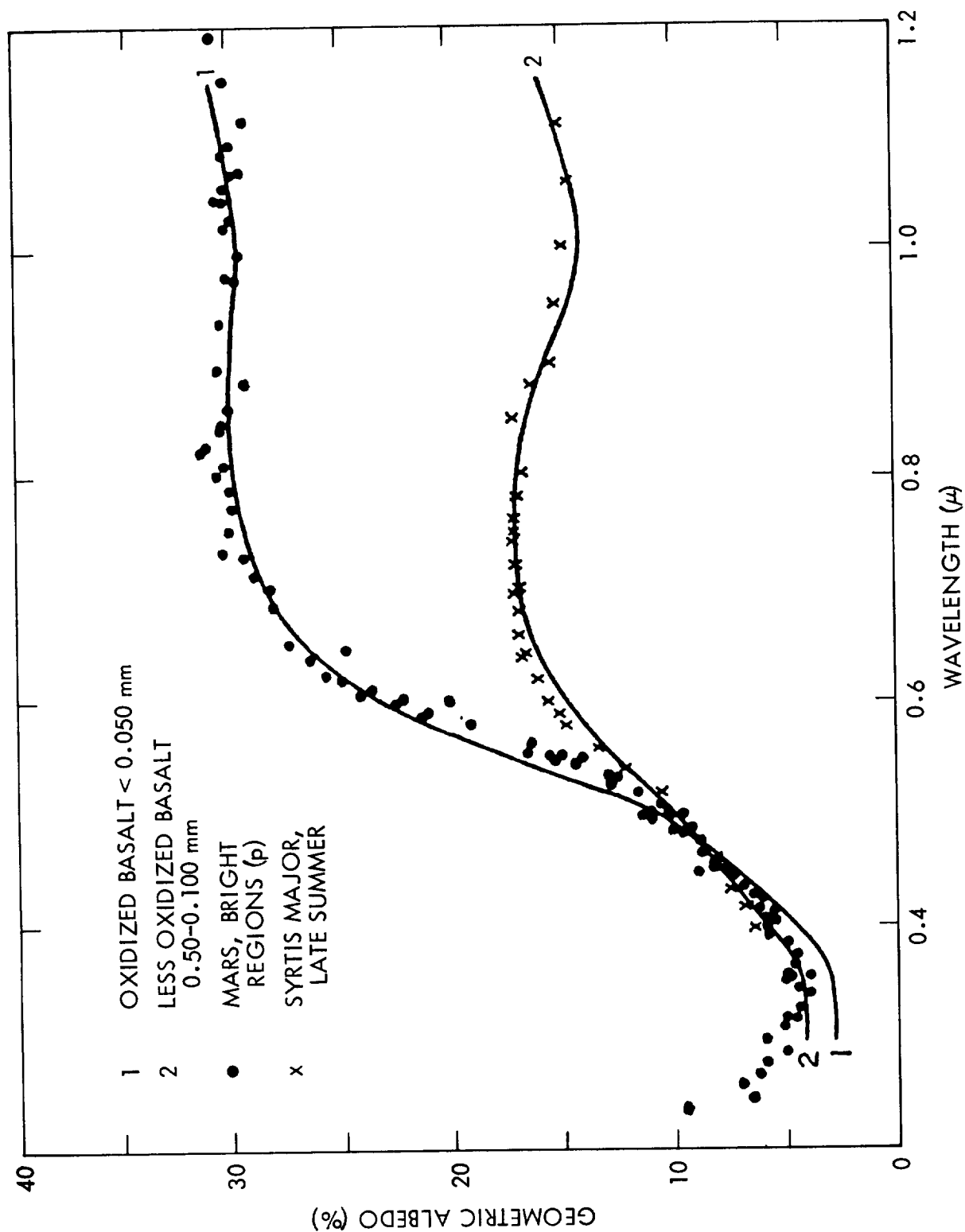


Fig. 4. Simulation experiments with oxidized basalts for the spectral geometric albedo of Martian bright and dark areas (Adams and McCord, 1969).

on Mars surface. In addition, the traditional pattern of dark and bright areas would necessarily have been created and maintained by an atmospheric supply of polymer. And more fatally, beyond 1.0μ the polymer spectrum diverges from the Martian one.*

Despite the preceding objections, the polymer hypothesis is still appealing to some chemical experimenters. Perls (1971), for example, critically examined and enlarged the C_3O_2 polymer hypothesis in an attempt to explain a number of Martian phenomena, both on the surface (seasonal changes) and in the atmosphere (large yellow clouds, blue clearings, seasonal variation of water vapor, etc.). Assuming the C_3O_2 compound is geochemically stable over long periods of time, Perls recognizes still the difficulties encountered by his 'working' hypothesis, and has enumerated many atmospheric constraints. Furthermore, he proposes additional laboratory experimentation as a means of verifying this hypothesis.

Neither the gaseous monomer C_3O_2 nor the polymer $(C_3O_2)_n$ have been detected in any spectra of Mars, whether taken by Earth-based telescopes at the highest resolutions (IR interferometry of Beer et al., 1971) or obtained by Mariner 1969 (IR spectrometry of Horn et al., 1972). These investigators placed a very low upper limit on the abundance of C_3O_2 gas in the Martian atmosphere (200×10^{-4} and 32×10^{-4} , respectively). Their results should seriously restrict the possibility of widespread distribution of the polymer on the Martian surface.

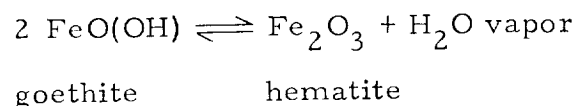
Distribution of Martian Surface Materials: Preliminary Results

Binder and Jones (1972) performed a Mars mapping program of wideband spectrophotometry, using 10 channels over the 0.6 - 2.3μ region, to obtain further data on the distribution of surface materials. (See Section 3.2 on Photometry.) The resulting spectral albedo curves obtained for 150 well-distributed regions (at spatial resolution of 300 - 500 km) fell into two distinct and uniform color/albedo groups, corresponding to the bright areas and dark areas as surface units. They interpreted this distinction as indicating that "the surface of Mars consists of basically only two types of materials," characterizing two lithologic provinces, bright and dark areas. Using laboratory comparison data (0.6 - 2.3μ) they concluded that the general color of the two unit groups is due to a limonite stain coating the basic rock materials (basalts, andesites) or soil particles. This conclusion was consistent with prior findings by other investigators. Binder and Jones further indicated that the small color difference (in the 1μ region) indicates that the dark areas are "richer in olivine and/or pyroxene" than the bright areas. However, in their testing they found that "soil particle grain size plays virtually no role in the albedo for limonite-stained materials." The difference between the two basic lithologies would be small, such as basalt versus andesite or peridotite.

*Cutts (1971) noted from his Mariner 7 tricolor-reflectivity plots that "the light and dark areas cannot be explained as simply different polymers of carbon suboxide"; i. e., various increases in its degree of polymerization.

Stability of Goethite on Mars

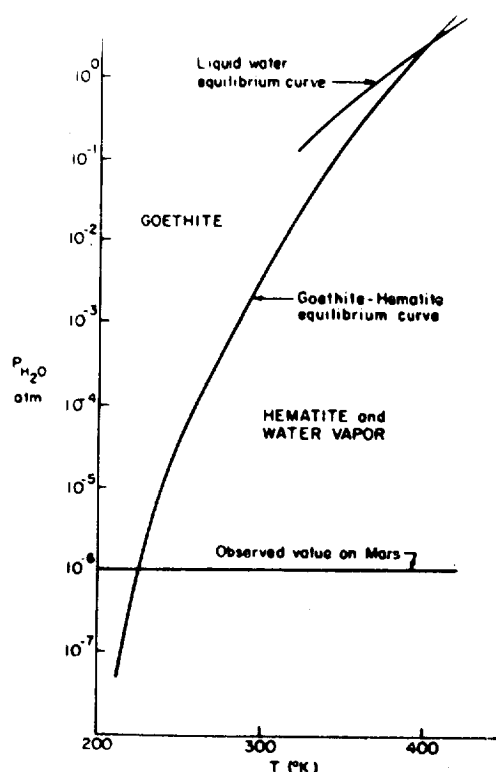
From the reflectance spectra, ferric oxides appear to be normal constituents of the bright areas top material, with amounts in the order of 1% or less. These oxides may be present in the mineralogical form known as goethite $\text{FeO}(\text{OH})$, or rather its impure variety, limonite. However, goethite or limonite should be subject to dehydration under the very low partial pressures of water vapor, and the question arises as to the stability of goethite on Mars. Therefore, it was necessary to investigate the system:



and perform exact thermodynamic calculations to determine the equilibrium water vapor pressure-versus-temperature curve in presence of these two minerals.

Preliminary estimates were made by Adamcik (1963), who concluded that goethite was sufficiently stable and that the system could well act as a buffer to the Martian H_2O vapor in the atmosphere. However, his estimates were severely criticized by Fish (1966) and O'Connor (1968) on the basis of new calculations proving goethite too unstable.

Recently the problem was treated anew more exactly and more comprehensively by Pollack et al. (1970a and 1970b). Not only did they produce improved thermodynamic calculations of the p versus T curve, but they also investigated the kinetics of the hydration/dehydration process and applied their results to conditions prevailing in the subsurface soil layers of Mars. Their vapor pressure equilibrium curve is shown in Fig. 5. The dehydration rate of goethite was found to be very slow (the time τ_d for dehydration to 1/e of the original weight for powdered goethite with an average $\sim 50 \mu$ particle size, typical of bright areas, was 67 hours at 225°K). Application to Mars confirmed that goethite would be unstable at the surface itself under the heat of daytime, but would be stable deeper within the topsoil layers where the heat wave is damped out and the temperature remains constant and low (about 200°K). (See Section 3.1 on Thermal Properties.) If the top layers are stirred relatively frequently by winds and cyclones, i. e. "dust storms," dust devils, or the like, then the surface and subsurface can be considered coupled, with the result that goethite can appear on the surface, where it only slowly and partially dehydrates before the next storm buries it again, permitting it to rehydrate. To the authors, this plausible Martian hydration/dehydration cycle for goethite (and/or possibly other hydrated minerals) appears to be balanced because the dehydration time is much greater than the 'characteristic' time for vertical mixing by winds or cyclonic storms. And, provided goethite or limonite is sufficiently abundant on Mars surface, it may even assume the role of long-term regulator or buffer (over millions of years) of the atmospheric water vapor content — because this goethite "would contain much more water than is present in the atmosphere and possibly in the polar caps." (Pollack et al. 1970b.)



At a given temperature T when the actual partial pressure of water vapor p_{H_2O} lies below the equilibrium curve, hematite is stable and goethite decomposes to hematite and water vapor; and conversely when p_{H_2O} is above the curve.

Fig. 5. Equilibrium vapor pressure curve for the goethite-hematite system. Pollack et al. (1970b)

3.4.3 Adsorption of Volatiles: CO_2 and H_2O

The highly particulate nature of the Martian epilith, at least in the bright areas, suggests that adsorption of atmospheric gases may occur to a very significant extent. This phenomenon could be a major mechanism for storing key volatiles such as CO_2 and H_2O especially at nighttime or when the temperature is low. Conversely, desorption would occur during daytime or when temperature rises, releasing volatiles from the topmost few cm of epilith. Such an adsorption-desorption cycle may not only have meteorological consequences but should be of vital importance to the metabolism of possible microorganisms residing in the soil. The few meters of epilith below could thus store more or less permanently a significant amount of water, in order for the epilith to be in physical equilibrium with the atmosphere.

The extent of the adsorption will depend generally upon the temperature, the relative pressure of the gas, and the amount, state of pulverization (or porosity) and adsorptive properties of the material. Thus, the larger the internal surface area (porosity), the lower the temperature, and the greater the relative pressure of the gas at that temperature, the more gas is adsorbed.

CO₂ Adsorption in a Bright Area: Experiments and Calculations

Davis (1969) made a conservative estimate of the amount of CO₂ adsorbed in a typical bright area under reasonable assumptions of temperature, partial pressure of CO₂ and adsorptive properties of the Martian dust assuming a particle size of diameter 2.8 μ (value given by Koval and Morozhenko, 1962). Using Brunauer et al. (1938) measurements of CO₂ adsorption on silica gel, he calculated that the dust adsorbs and desorbs (upon solar warming) 4.4×10^{-6} mole of CO₂ per cc of bulk volume (particles + voids) of particulate material. This is a significant amount for a tenuous atmosphere.

Fanale and Cannon (1971), experimenting with vacuum-pulverized basalt of mean particle diameter 22 μ to simulate the Martian epilith material, found a very high adsorptive capacity: 6.75×10^{-5} mole/cc of material under 6.5 mb CO₂ and at 196°K (-77°C). They produced adsorption isotherms for this material under a CO₂ pressure range of 1-25 mb and at three different temperatures (-77°, 0°, and 29°C). Applying this data to Mars, and assuming an epilith depth of 10 meters and bulk density 1.5 g cm⁻³, they found that about 1500 cc STP (3 g) of CO₂ can be adsorbed per cm² of a hypothetical 15 meter epilith column at 196°K, or about 1000 cc STP (2 g) of CO₂ at 210°K.

H₂O Adsorption: Experiments

Fanale and Cannon (1971), experimenting with the same pulverized basalt, predict an even greater adsorption of water vapor than that of CO₂ on Mars. An adsorption of 8.5 mg of H₂O vapor per gram, at 29°C, was noted when the partial pressure of H₂O vapor was almost at the saturation value (99%). They calculated that many monolayers of H₂O were then adsorbed. The number of H₂O monolayers absorbed, according to them, is determined primarily by the relative pressure of H₂O (ratio of ambient to saturation pressure; i. e., the relative humidity) and only very moderately by temperature.* Extrapolating to a Martian atmosphere containing 25 precipitable micron H₂O and with a base at ~200°K (where, they remark, would prevail a near-saturation humidity), a similar amount of H₂O adsorption could be expected at the proper season.

The relative humidity being very sensitive to temperature at constant partial pressure H₂O, only a slight warming (10° or 20°) of the subsurface (above the saturation temperature) would cause rapid desorption of most of the H₂O. The released desorbed H₂O vapor could then condense in the colder lower atmospheric layer as ice crystals, fog. The authors propose that at least some of the (morning) whitenings seen in the Martian tropics may be explained by such a diurnal desorption of H₂O vapor from the soil.

*There is some evidence that this is the case, at least for some adsorbers, down to about -30°C. Data on H₂O adsorption far below the freezing point is exceedingly sparse, however, and that for adsorption on free silicate surfaces under such conditions is virtually nonexistent (Fanale, 1971b).

3.4.4 Martian Permafrost: Speculations

The possibility that the Martian subsurface holds appreciable quantities of H₂O permafrost (permanently frozen ground) is very attractive, especially to biologists. The idea has been advanced by a number of investigators, for example: Lederberg and Sagan (1962), Strughold (1965), Salisbury (1966), and Katterfeld and Frolov (1968). The biologists are contemplating a possible source of soil moisture indispensable for the survival of a hypothetical Martian microbiology or microflora. The geologists are interested in explaining some of the morphology (for example: chaotic terrain) photographed by the Mariners. (Note: No typical terrestrial permafrost forms were seen nor could be seen since the resolution was insufficient by at least an order of magnitude. A resolution of one to ten meters would be necessary.) In any case, if permafrost beds or layers truly were present extensively on the planet, our concepts about the development of its surface and atmosphere would need serious revision. Hence, the appropriateness of examining speculations about the possible occurrence of Martian permafrost.

Formation of permafrost presupposes three conditions are met:

- 1) A porous soil or subsurface material
- 2) A supply of water (atmospheric or subterranean)
- 3) Subfreezing temperatures most of the time

On Mars, conditions 1) and 3) are certainly fully met. Condition 2) is partially met. There is definitely atmospheric water vapor, in very small variable amounts, but is the amount sufficient? Ground (juvenile) water is not known yet to occur. From terrestrial analogy, juvenile water usually occurs in areas where the crust is active (outgassing, volcanism, ...); the amount of released H₂O would be adequate but the occurrence most likely localized.

The presence of permafrost on Earth produces a number of very small characteristic topographic features at the surface (in arctic regions), which are due to two main processes (Wade and DeWys, 1968):

- 1) Frost-heaving
- 2) Ice/sand wedging

The typical forms produced include patterns of polygonal ridges and troughs, conical and irregular mounds, etc.

Wade and DeWys (1968) hypothesized that such forms could well develop on Mars, at almost any latitude, provided there is an adequate supply of water. They rely primarily on the availability of subterranean water (juvenile water from outgassing of the interior), rather than on atmospheric (meteoric) water. This juvenile water would come up from the warm depths below and freeze upon reaching the base of the permafrost layer, thus adding to its thickness gradually. The patterned ground develops from thermal contraction and expansion of the layer, with subsequent filling of the resulting cracks with ice or sand, etc.

Permafrost From Atmospheric Water: Calculations

Leighton and Murray (1966) calculated the behavior of Martian water vapor assuming only an average abundance of $\sim 10^{-3}$ g cm $^{-2}$ or 10 μ of precipitable H $_2$ O in the atmosphere. They showed that under the known regime of insolation (with resulting average annual temperatures below freezing at all latitudes) much permafrost H $_2$ O (ice) could be locked in the subsurface of the polar and even temperate regions (down to 40°-50° latitude). Only atmospheric (meteoric) water vapor was used. The mechanism postulated was the following: if the water vapor can penetrate into the porous soil to a depth of at least a few meters, it may reach a region where the temperature is perpetually below the 190°K condensation temperature which is necessary to condense the H $_2$ O vapor at the partial pressure of 3.7×10^{-4} mb, corresponding to the 1×10^{-3} g cm $^{-2}$ abundance (Fig. 6). The water would tend to migrate poleward condensing as permafrost. After millions of years the trapping layers would be saturated with ice and extend downward tens of meters, so that "possibly several hundred grams of H $_2$ O per cm ^{3} would be present in the pores of the soil." They estimated that "the top of the permafrost layer should be only a few centimeters below the actual surface except near the (lateral) boundaries" (40°-50° latitude), and that at a given latitude it should be shallower in the Northern than in the Southern Hemisphere. See Fig. 7. (Note: this depth difference would define the amount of water potentially transferable between hemispheres during the 50,000-year effective precessional cycle. They did not calculate this amount.)

Possible Frost-Heaving Caused by Atmospheric Water

Otterman and Bronner (1966) had suggested that frost-heaving phenomena (producing microroughness of the surface because of textural changes associated with freezing) could account for the dark areas of Mars. The mechanism suggested was: atmospheric H $_2$ O (vapor) adsorbed soil H $_2$ O (water) permafrost frozen H $_2$ O (ice).

Anderson et al. (1967) examined this possibility, using experimental data on the adsorption characteristics of sodium montmorillonite for water vapor and liquid (from Mooney et al., 1952), and concluded that Otterman and Bronner's hypothesis was "highly improbable" on the scale of dark areas. Exception, however, was made for the unlikely (unrealistic) case where Martian soils contain great quantities of strongly deliquescent salts, since these would attract and retain liquid water in the soil interstices. (Note: Such salts not only lower the freezing temperature of the soil water solution, but also can "greatly increase the water vapor sorption capacity of any soil material" — Anderson et al.)

Anderson et al. (1967), in their article, did not consider the possibility of frost-heaving caused through ascent and freezing of juvenile water from the interior.

3.4.5 Liquid Water (at or Near Surface)

Pure liquid water normally cannot exist for very long on the Martian surface. This follows from the classical phase diagram of water (Fig. 8) and the fact that the average surface pressure on Mars is about 5.5 mb; i.e., below the

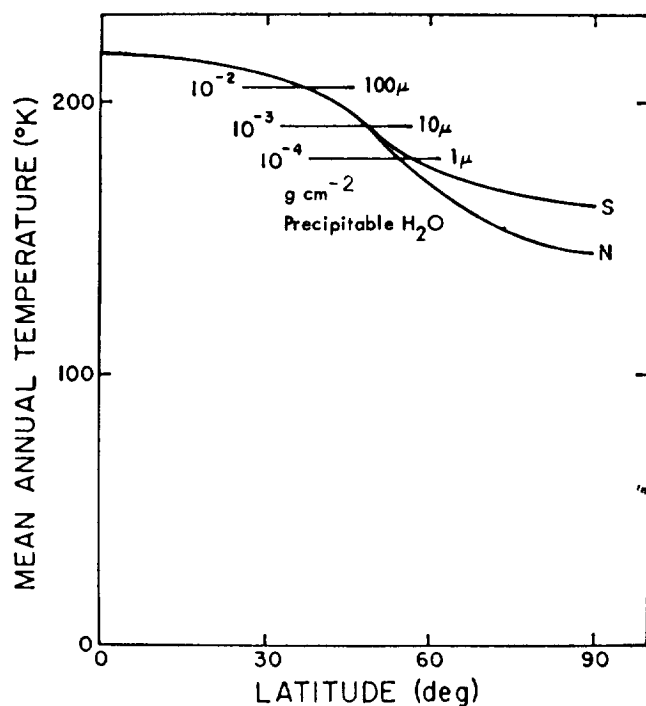


Fig. 6. Mean annual temperature as a function of latitude, with indication of condensation temperatures of water vapor for three atmospheric abundances (Leighton and Murray, 1966).

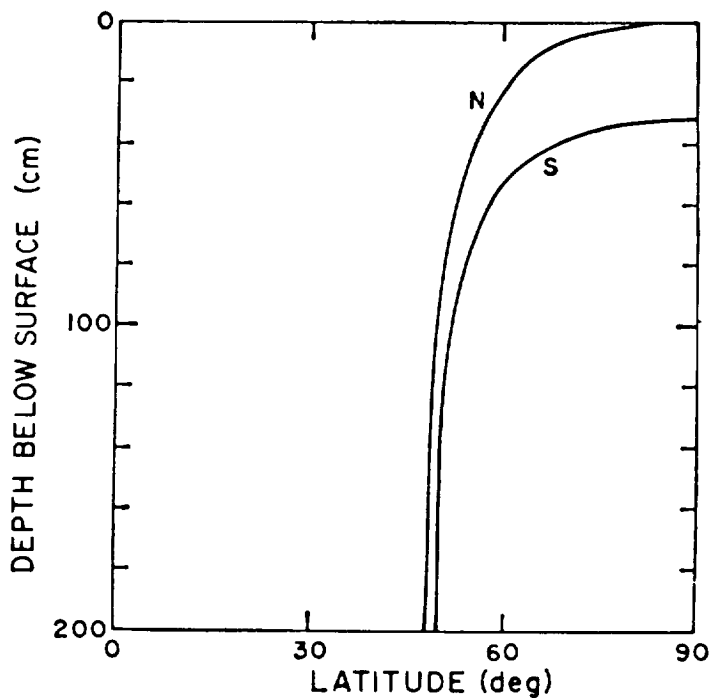


Fig. 7. Depth of top surface of H₂O permafrost, as a function of latitude. The difference in depth between the two hemispheres defines an amount of water that should be exchanged between the hemispheres or during the 5×10^4 -year precessional period (Leighton and Murray, 1966).

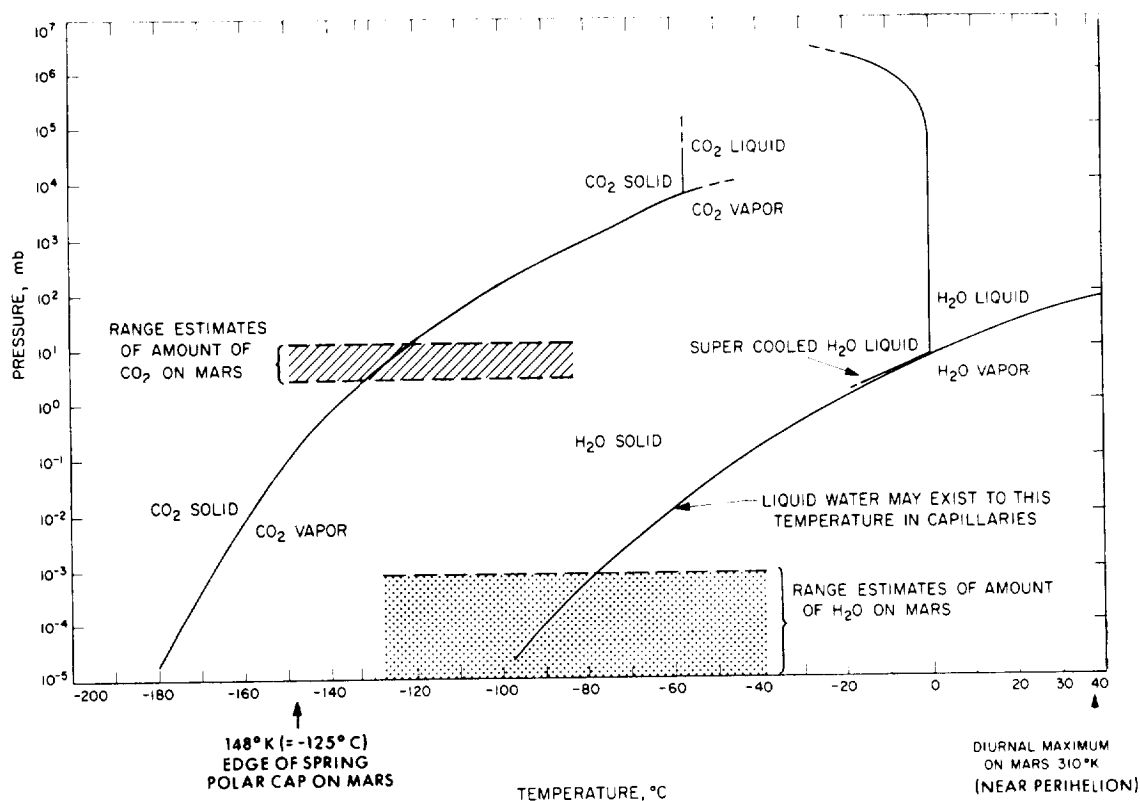


Fig. 8. Phase relationships of CO_2 and H_2O .
(modified after Wade and De Wys, 1968)

triple point pressure of water ($p_t = 6.105 \text{ mb}$). In low areas where surface pressure is as high as 8 mb (or 10 mb), liquid water would survive for a longer period (at a temperature just above freezing or 0°C) but would still be evaporating very rapidly. (Note that the rapid evaporation may create a protective layer of ice in places, retarding the evaporation.)

Concentrated solutions of hygroscopic salts (FeCl_3 , CaCl_2 , NaCl , ...), by significantly depressing the freezing point (by 10° to 50°C) as well as the equilibrium vapor pressure (to below 1 mb), could certainly exist for much longer periods. Such pools could form locally at hydrothermal locations, but would of course undergo the diurnal and seasonal freezing and thawing cycles.

The availability of surficial liquid water could occur from the insolation melting of permafrosts which are composed of eutectics of such salts, provided the permafrost "table" is near the surface (a few centimeters below), but it is more likely that it would originate from subterranean sources with subsurface temperatures kept above freezing by internal (e.g., radioactive) heating.

Surface H_2O frost (condensed from the atmosphere) is not expected to contribute liquid (melt) water under insolation, because calculations (Ingersoll, 1970, for example) show that sublimation will take place faster than melting under the known Martian surface conditions.

Subsurface H₂O frost in soil interstices and capillaries can produce a liquid phase (from buildup of partial H₂O vapor above p_t), provided the diffusion rate is low, but then this would contribute hardly any liquid water to the surface. See, for example, Sagan et al., (1967) or Smoluchowski, (1968).

Direct condensation from the atmospheric H₂O vapor into liquid droplets on surface "active" spots is possible but would produce only tiny (submicron-sized) droplets, as shown by Mukherjee (1968).

CHEMICAL PROPERTIES OF THE POLAR CAP DEPOSIT

The long-standing question of the chemical nature of the Martian polar caps is finally reaching settlement after the 1969 flyby of Mariner 7. Of the two acceptable theories as to the bulk of its constitution, H₂O (Lowell, 1906, repropounded by Miyamoto and Hattori, 1968) or CO₂ (Wallace, 1907, revived by Leighton and Murray, 1966 and Leovy, 1966), the latter is undoubtedly the correct one. The former, however, also has its place, simultaneously, but to a much more restricted degree. From the evidence listed below, it can be stated today that the Martian polar caps are composed mainly of solid carbon dioxide — the major constituent — with solid water also, as a minor constituent. Since 1963 the following observational and theoretical evidence has been rapidly accumulating toward this view.

- 1) Kaplan et al. (1964): Spectroscopic determination of 4 mb of CO₂ and 14 μ of precipitable H₂O vapor over Mars.
- 2) Kliore et al. (1965): Mariner 4 radio occultation determination of an approximately 5 mb total surface pressure and inference of at least 50% CO₂ atmosphere.
- 3) Leighton and Murray (1966): Theoretical calculations indicating that polar temperatures fall low enough to precipitate CO₂, and that the polar caps probably are predominantly CO₂ plus minor amounts of H₂O.
- 4) Leovy (1966) and Leovy and Mintz (1969): Calculations of the minimum atmospheric temperatures required to prevent CO₂ condensation and simulation of the Martian atmospheric circulation respectively led to essentially the same conclusion.
- 5) Morrison (1968): Re-analysis of the Sinton and Strong (1960) IR radiometric temperatures, permitting extrapolation for the extended cap's edge (60° latitude) to a CO₂ condensing temperature (145°K).
- 6) Kieffer (1968): Laboratory IR spectra of CO₂-H₂O frosts indicating that very small amounts of H₂O can mask the characteristics of the solid CO₂ spectrum, thus rendering illusory the earlier conclusions of Kuiper (1952) and Moroz (1964) in favor of an H₂O cap.*

*Polar cap spectra obtained from Earth are limited to those of Kuiper (1952) and Moroz (1964) who concluded that the caps consisted of H₂O.

- 7) Schorn et al. (1969): Spectroscopic observations of greater than average amounts of precipitable H₂O vapor over the late spring/early summer rapidly shrinking polar cap (35 micron precipitable H₂O).
- 8) Sharp et al. (1971): Mariner 7 TV observations of the morphology of the expanded South Polar Cap revealing interior frost cover thicknesses in the order of meters or more.
- 9) Neugebauer et al. (1971): Mariner 7 IRR determination of the very low (148°K) and constant daytime temperature of the sublimating expanded South Polar Cap.
- 10) Herr and Pimentel (1969, 1971): Mariner 7 IRS identification of spectral absorption features characteristic of solid CO₂, plus the possibility of H₂O and impurities for the South Polar Cap composition.

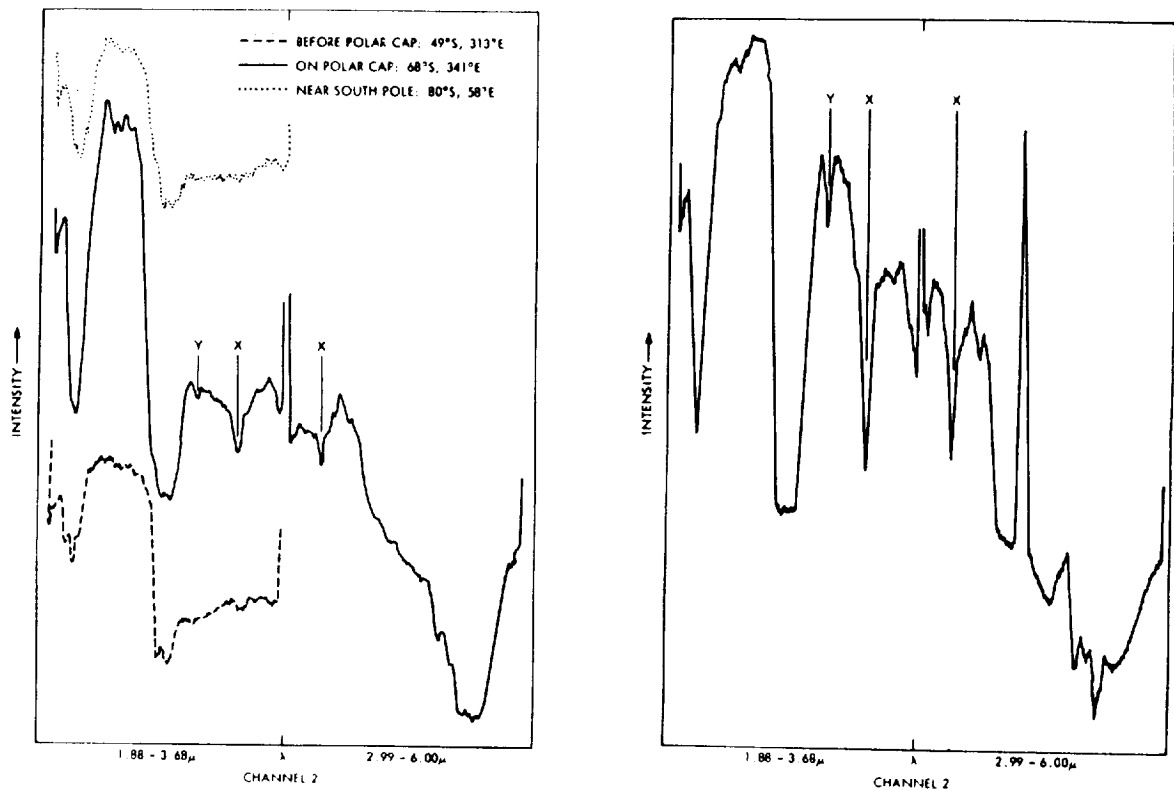
3.4.6 South Polar Cap: Mariner 7 IRS Results

On August 5, 1969, when the South Polar Cap was starting to shrink during early Martian spring, the IRS channel 2 of Mariner 7 recorded some 19 spectra. These spectra between 1.88 and 6.00 μ were obtained over the cap from 61° to 80°S latitude with an areal resolution of about 120 km square. Although final analysis of the data has not been completed, it has been concluded that the dominant absorption features are "obviously attributable to solid CO₂" (Herr and Pimentel, 1969). Typical polar cap spectra is shown in Fig. 9, with comparison laboratory spectrum. Besides the common solid CO₂ features, such as the 2.0 μ (4900 cm⁻¹) intense sharp band, two distinct new features, labelled X and Y, were noted near 3.31 μ (3020 cm⁻¹) and 3.03 μ (3300 cm⁻¹) respectively. The maximum intensity of these bands occurred at about 68°S, 19°W, not far from the cap's edge (61°S). These bands (X and Y), which happen to match some bands of methane and ammonia, appear to be previously unreported spectral features of solid CO₂ in thicknesses of several millimeters, according to the laboratory experiments of Herr and Pimentel (1969). These two absorptions correspond to "forbidden" transitions of the CO₂ molecule (which violate the spectroscopic selection rules). Pimentel and Herr tentatively attributed these transitions to lattice imperfections in the deposit's microstructure. It was noted that these features disappear further south, nearer the pole (~80°S).

3.4.7 Near-Infrared Reflection Spectra of CO₂-H₂O Frosts

For the purpose of interpreting the pre-Mariner 1969 spectra (Kuiper, 1952; Moroz, 1964) of the Martian polar caps, Kieffer (1968, 1970a, b) performed laboratory measurements on the spectral reflectance from 0.8 to 3.2 μ of the frosts likely to occur on Mars: pure CO₂, pure H₂O, mixed CO₂-H₂O, and H₂O on CO₂ frosts in a wide range of grain sizes. His main results are summarized below. (For the spectra themselves, see the original papers.)

- 1) CO₂ Frosts: Uniformly high reflectance (>90% at λ below 2.5 μ) from 0.8 to 3.2 μ except for two major absorption bands centered at 2.0 and 2.7 μ (quite broad: 2.6-2.8 μ usually). These two bands, which are the triplet and doublet observed in the gas phase, deepen in absorption as grain size increases, while new, weaker features unique to



NOTE: A portion of the 3 μ region is recorded twice on either side of the spectrometer spike.

Fig. 9. Near-infrared spectra of the South Polar Cap by Mariner 7 (left) and comparison laboratory spectrum of solid CO₂ at 77°K (right) (Herr and Pimentel, 1969).

the solid phase start appearing (such as a strong one at $2.62\ \mu$, also $2.85\ \mu$, and weak ones at 1.87 , 2.12 , 2.28 , 2.34 , 2.90 , and $2.03\ \mu$). The $2.7\ \mu$ band is saturated (1% reflectance) for frosts of textural scale $50\ \mu$ grain size. The 2.9 to $3.2\ \mu$ continuum is very sensitive to H_2O impurity.

- 2) H_2O Frosts: Broad absorptions centered at 1.56 , 2.04 , and $3.0\ \mu$ for fine frosts especially, and saturation adsorption from 2.9 to $3.2\ \mu$ for all frosts. The reflectance showed great variability with growth conditions. Compared to CO_2 frost, the H_2O frost spectra have lower near-IR reflectance, generally decreasing from 0.8 to $3.2\ \mu$ (and especially with thin, fine H_2O frosts).
- 3) Mixed CO_2 - H_2O Frosts: Small amounts of H_2O have a strong effect on CO_2 spectra, an effect which increases with grain size. When H_2O is $>10\%$ by mass, it becomes difficult to identify CO_2 , because the H_2O features predominate. The presence of CO_2 is revealed only by the high reflectance at $2.5\ \mu$ for fine frosts, and only by minor absorption detail at 2.0 and $2.7\ \mu$ for coarse frosts.
- 4) H_2O on CO_2 Frosts: The effect is even more drastic, since a surface layer of only a few $mg\ cm^{-2}$ of H_2O will mask an underlying thick CO_2 deposit (about $7\ mg\ cm^{-2}$ will suffice; with $1\ mg\ cm^{-2}$, H_2O already subdues the CO_2 features).

3.4.8 Possible O_3 Adsorption by the Polar Cap: Mariner 7 UVS Results

All 45 of the Mariner 7 UVS spectra of the spring South Polar Cap showed a broad absorption band centered at $2550\ \text{\AA}$ with a shape corresponding well to that expected from ozone O_3 (Hartley continuum band between 2000 and $3000\ \text{\AA}$); see Fig. 10 from Barth and Hord (1971). Ozone is a normal product occurring in the photochemistry of CO_2 . This ozone could be either in the atmosphere, preferentially over the cap, or adsorbed (or trapped) in the solid CO_2 of the cap itself as suggested by Broida. In the first case, the amount of atmospheric ozone was calculated by Barth and Hord to be $1 \times 10^{-3}\ cm\text{-}atm$ or 3×10^{16} molecules cm^{-2} of O_3 (or a mixing ratio of $\sim 10^{-7}$ for O_3/CO_2). In the second case, the amount of adsorbed ozone could be estimated on the basis of the laboratory experiments of Broida et al. (1970), but no figure is available.

The polar cap CO_2 might also adsorb or trap other gases (such as O_2 , CH_4 , NH_3 , ...), if present in Mars atmosphere, and serve as a "sink" for these gases (Barth and Hord, 1971).

3.4.9 Speculations on the Composition and Structure of the Polar Caps

The brilliant white material constituting the Martian polar caps is now generally believed to be the icy condensation products of the abundant gaseous carbon dioxide and the scarce water vapor unquestionably present in the Martian atmosphere. The saturation vapor pressure curves of solid CO_2 and H_2O (Fig. 8) show that, under the prevailing Martian mean surface pressure of $6.5\ mb$ (Kliore et al., 1969), and a H_2O/CO_2 mass ratio of 10^{-4} , the condensation temperatures are very low: for CO_2 it is $148^\circ K$, while for H_2O it is

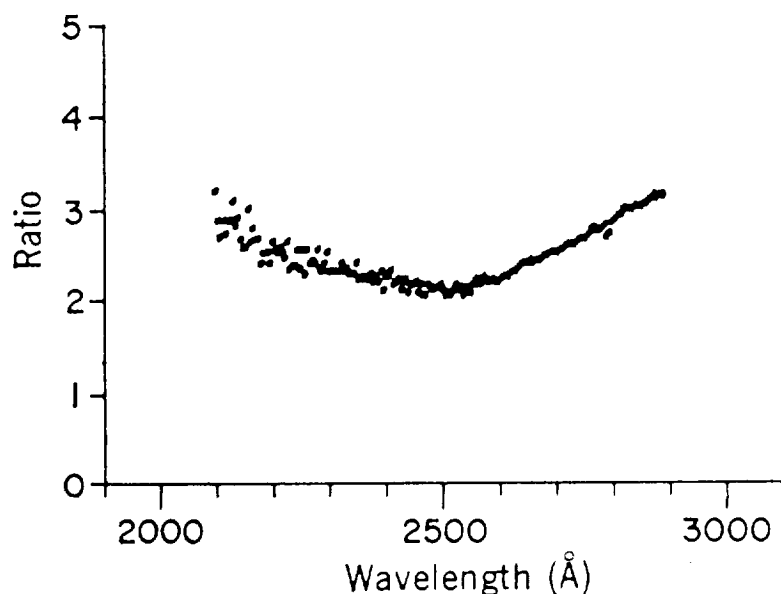


Fig. 10. Ratio of reflectance of polar cap to reflectance of a desert region. The minimum at about 2550Å suggests absorption by ozone. Barth and Hord (1971)

~210°K. (The condensation temperature T_c varies in the same sense as the surface partial pressure.) Thus, normally solid H_2O should first condense out as the temperature goes down and form snow or ice fog in the atmosphere or frost on the cold ground. These products should be finely divided since the atmospheric H_2O abundance is very low. Then, at a temperature of 153°K (if pCO_2 is still 6.5 mb), according to the Miller and Smythe (1970) experiments (see Fig. 11), the finely divided H_2O ice combines with gaseous CO_2 rather rapidly (several hours) to form the carbon dioxide clathrate hydrate $CO_2 \cdot 6H_2O$, which also has the appearance of ice. (All the H_2O ice becomes converted into $CO_2 \cdot 6H_2O$ hydrate.) Finally, at the slightly lower temperature of 148°K, gaseous CO_2 condenses out into solid CO_2 in the presence of the hydrate, so that both coexist. The hydrate is stable down to about 121°K, below which temperature it dissociates into H_2O ice and CO_2 ice. Thus, if the temperature in the Martian polar regions remains above 121°K, the polar cap formed "can consist of water ice, water ice + CO_2 hydrate, or CO_2 hydrate + solid CO_2 , but not water ice + solid CO_2 " (Miller and Smythe, 1970). If the surface pressure is different (than 6.5 mb), one can find the exact combination or condensation temperatures (for CO_2 hydrate and solid CO_2) from Fig. 11, which shows the dissociation pressure curve of CO_2 hydrate and also the vapor pressure curve of solid CO_2 .

The above sequence of condensation products applies particularly to the formation of the polar cap in wintertime. It appears that the composition of the formed cap (at end of winter) may well be layered: the lower layers being rich in CO_2 hydrate and representing the "fall" cap, while the upper layers would be rich in solid CO_2 and represent the "winter" cap. The formed cap, however, will have a bulk composition of solid CO_2 (and a small fraction of CO_2 hydrate) since the atmospheric H_2O vapor ratio is always small. The composition of the shrinking cap in late spring-early summer is expected to be quite different from

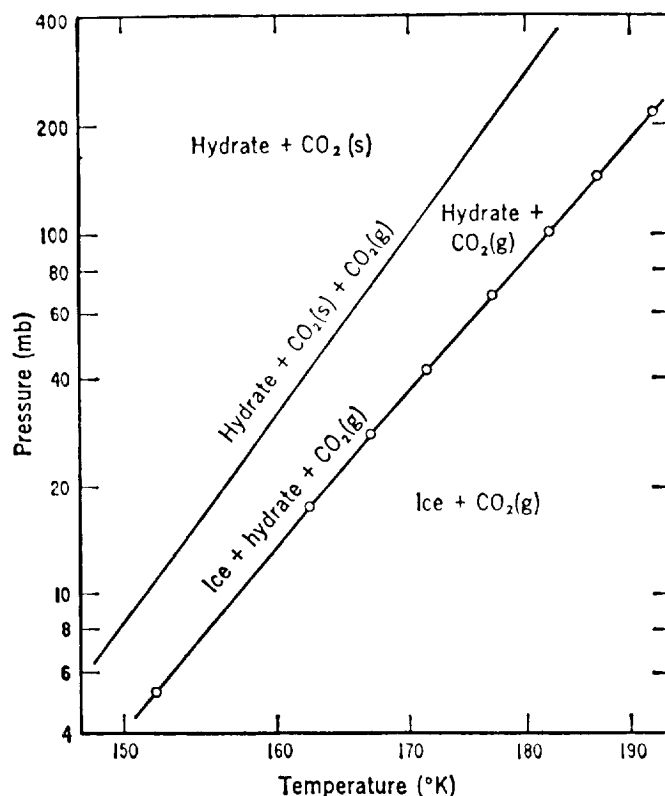


Fig. 11. Phase diagram of carbon dioxide hydrate. Experimental dissociation pressure measurements, O; vapor pressure of solid CO₂. Miller and Smythe (1970)

that of the winter cap for the same physical reasons. If one considers the more rapid sublimation of solid CO₂ than H₂O ice – (resulting from the dissociation,* under the higher temperatures, of the CO₂ · 6H₂O hydrate into H₂O ice and CO₂ gas) – this cap should with the advancing season more and more rapidly enrich itself in its H₂O ice proportion so that before its final late summer stage the remnant cap should exhibit a bulk composition closer to H₂O ice (with a small fraction of CO₂ hydrate remaining). The Mariner 1971 orbital mission might determine this for the remnant south cap. (The Mariner 7 in 1969 viewed an early spring south cap.) In some places however, the summer shrinking south cap may be covered with dust layers protecting the rapid CO₂ sublimation, since major dust storms usually occur in southern late spring and early summer (see Section 4.2 on Seasonal Activity).

*This dissociation, taking place at 153°K under 6.5 mb, is the regular hydrate dissociation with temperature rise. The dissociation at temperatures below 121°K is an anomaly – known only for this hydrate – and caused by the fact that its dissociation pressure is greater than the vapor pressure of solid CO₂ below 121°K (Miller and Smythe, 1970).

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3.5 MORPHOLOGY AND PROCESSES

INTRODUCTION

Prior to our era of spacecraft and radar exploration of planetary surfaces, only speculations (based on poor-resolution telescopic observations and using lunar and terrestrial analogies) could be evolved as to the morphology of the surface of Mars. In 1965, Mariner 4 revealed the presence of many craters, as on the Moon, but the Martian craters exhibited significant erosion. Mariners 6 and 7, in 1969, while confirming the wide extent of cratered terrain, discovered two new types of essentially uncratered terrain: the chaotic terrain of Pyrrhae Regio, and the featureless terrain of Hellas, which was found to be a basin. Mariners 6 and 7 also investigated the relationships between dark and bright areas, established the nature and estimated the thickness of the South Polar Cap, and apparently dispelled the lingering myths about the Martian canals. Radar observations had separately established the topography of the northern equatorial belt, and determined surface properties such as dielectric constant and average roughness.

With the flood of new information, speculations on a different level about the geology of Mars have replaced the older, rudimentary ideas. The present speculation will, in turn, be influenced by new data obtained from the current (1971) orbital missions.

Processes at work on the Martian surface and beneath it (subsurface), responsible for its morphology (other than atmospheric and impact modifications), still remain unknown or are very poorly understood. Some of these processes have apparently operated continuously or episodically, over very long times to shape the present distinct Martian surface. Other processes appear relatively more recent in the planet's history.

The following review attempts to present only the factual information about Martian morphology proper, as gathered primarily through examination of the near encounter (NE) pictures of Mariners 4, 6, and 7, which were taken several thousand kilometers away from Mars. The tableau presented here is very incomplete because of the limited surface coverage of the planet (less than 20%). Only some 80 total NE pictures were taken. A selection of Mariner 6 and 7 pictures is presented in Section 3.6, Photographic Atlas. The far encounter (FE) pictures, although obtained at coarser surface resolution, have provided a global survey which has permitted new maps to be drawn. As for the probable processes at work, this review is necessarily speculative in character, based on the present state of knowledge.

It must be mentioned that relatively few geological or morphological studies of Mars have been published since the Mariner 6 and 7 encounters. At present, there is little doubt that most geologists attracted by this subject are eagerly awaiting the more extensive information expected from a successful completion of the Mariner 9 orbital mission (and also from the Mars 2 and 3 Russian missions), before undertaking a comprehensive study of the Martian features and processes.

3.5.1 TOPOGRAPHY

The topography of substantial portions of the Martian surface has been established with a fair degree of reliability by Earth-based radar and by the infrared and ultraviolet spectrometers on board Mariners 6 and 7. The radar coverage, geometrically restricted to latitudes less than 25° , was mostly in the Northern Hemisphere, while the often-overlapping swaths of the Mariner IRS and UVS extended prongs deep into the Southern Hemisphere. Some locations were sensed or scanned by all three methods, which permitted a comparison of results. It was found that the data do not always agree; in fact, some of the discrepancies are rather notable (4 km). In such cases, preference has been given to the radar results, which should provide correct relative altitudes (along latitudinal scans around the planet) and are not affected by undetermined systematic errors caused by atmospheric (aerosols, etc.) and photometric (contrast) effects, as are the IRS and UVS results. The radar method is explained in Section 3.3, Radar Properties. The IRS and UVS methods are briefly discussed here, with indications of the best resolutions attained. An attempt is then made to summarize the topographic information obtained by these three methods. Indications on the 1971 radar results are also included. Additional Earth-based IRS measurements were also made by two teams (Belton and Hunten, 1971; and Wells, 1971 a), but the resolution is necessarily much coarser (order of 1000 km), and many sources of error (seeing, calibration, etc.) have apparently affected the results, which do not generally agree with those presented here.

Spectroscopic Methods

Infrared (Mariner IRS)

The infrared spectroscopic method measures the absorption of a prominent CO_2 band (2μ in Mariner IRS, or 1.05μ in Earth-based IRS) and derives, through laboratory curves of growth, the abundance of the CO_2 in the atmospheric path sampled. From the CO_2 abundance a corresponding surface partial pressure of CO_2 (at the base of the atmospheric column) is obtained, which is finally converted to topographic height above a reference level, upon adoption of an atmospheric model. (For the Mariner IRS data, a 100% CO_2 atmosphere, isothermal at 200°K , was chosen by Herr et al., (1970.)*)

The zero altitude chosen was that corresponding to $p_0 = 6.0$ mb. The best horizontal resolution (on ground) was 130×8 km. The resolution corresponds to the instrument's field of view ($2.0^\circ \times 0.23^\circ$) and on the slant range to the planet. The absolute accuracy claimed in heights measured was ± 1 km.

Ultraviolet (Mariner UVS)

The ultraviolet spectroscopic method measured the UV reflectance originating primarily from atmospheric scattering (molecules and possible small aerosols), which is taken as directly proportional to the total number

*The Mariner IRS results of Herr and Pimentel are being revised, with adoption of a more appropriate or realistic atmospheric model. No results have been published yet.

of scatterers in the atmospheric column sensed. This number is in turn converted to topographic height by means of an atmospheric model, as in the IRS method. Basic assumptions are (1) homogeneous scattering atmosphere, and (2) uniform ground reflectance.

The zero altitude chosen was that corresponding to $p_0 = 6.105$ mb (at the triple point pressure of H_2O). The best horizontal resolution was 140×14 km, but 300×30 km at the limbs. The relative accuracy claimed was 1%.

Summary of Present Topographic Information

The below-listed topographic highlights were obtained via all three remote-sensing methods. The information, categorized by data source, is related to the classical surface features (dark areas and bright areas as shown in Fig. 7), starting at 0° longitude and working eastward across the surface of Mars without regard to latitude. Comparison of the detailed surface pressure and derived altitude results from Mariner 6 and 7 UVS and IRS experiments is shown in Figs. 1, 2, and 3, from Hord (1971).

1) From the Mariner 1969 UVS and IRS, and the 1971 Radar Results

Deucalionis Regio, in its western half, bordering Pandora Fretum, is equally a high region (2-4 km) to both UVS and IRS; but this disagrees markedly with the 1971 radar information, indicating it is some 4 km lower. The 1971 radar traverses show the whole of Deucalionis Regio to gently slope from 1 to -3 km along its 2500-km length, parallel to the equator.

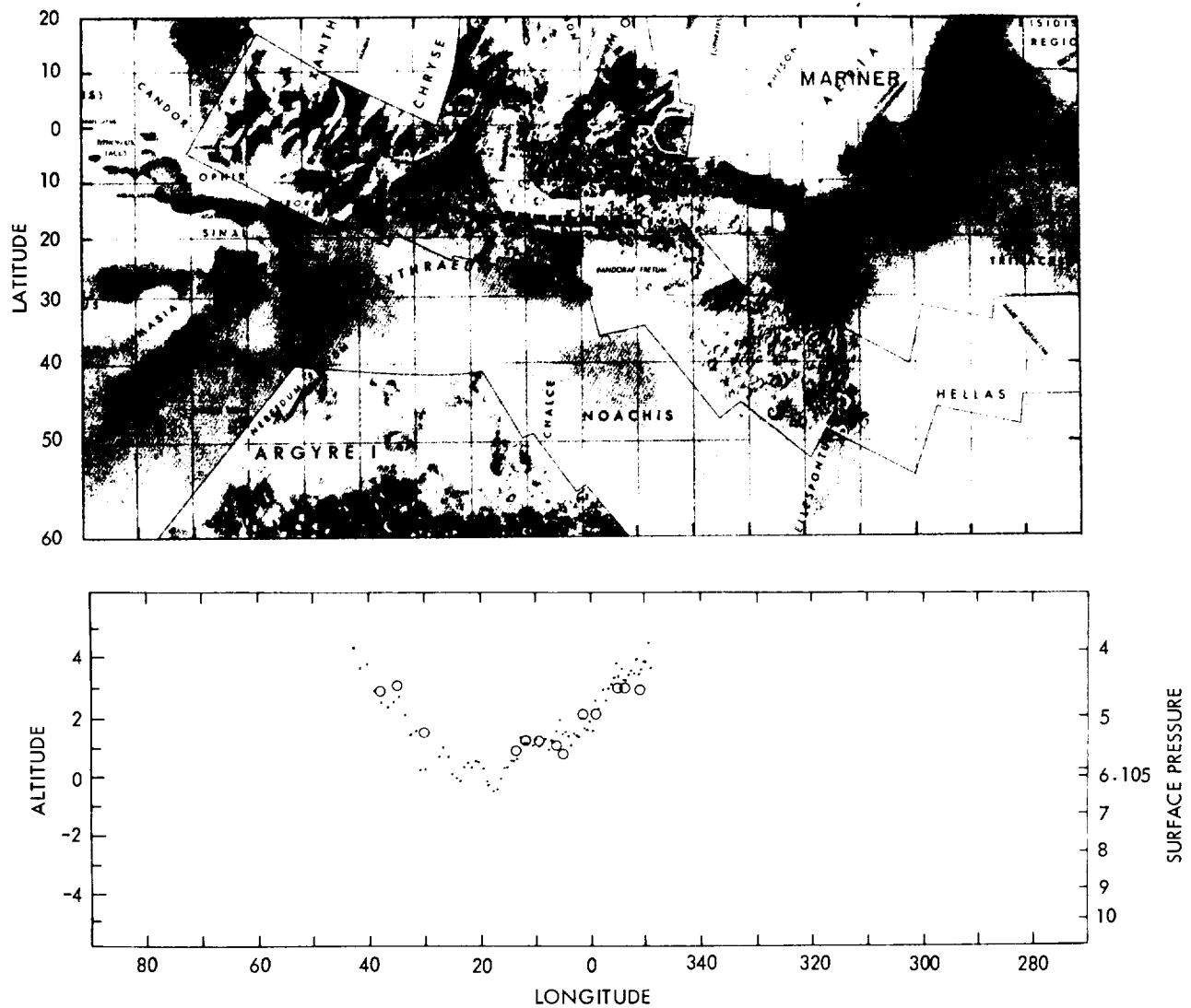
Pandora Fretum and from northeast Noachis desert to Hellespontus form a high plateau about 3-km high, stretching some 2000 km (UVS and IRS).

Hellas is a large basin with its central region as low as 3 km below mean or zero level (UVS and IRS). Its western edge in Yaonis Regio and Yaonis Fretum is a steep slope (looking toward Hellas, with a 4-km altitude difference over only 300 km (UVS).

Iapygia is at mean elevation (0 km) as is Trinacria to the east of it (radar 1971).

Northern Aurorae Sinus near Juventae Fons shows a greater disagreement of ~5 km between UVS (-3 km) and IRS (2 km). In Juventae Fons and northwest of it, however, the UVS and IRS agree, with altitudes of 2 to 3 km.

Argyre (north of Mare Australe) appears to be rolling terrain at medium elevation (UVS and IRS), and apparently slopes down toward Ogygis Regio (UVS).



The lower portion shows the comparison of the results, while the upper portion indicates the scanning tracks on the Martian surface.

Fig. 1. Mariner 6 UVS and IRS surface pressures and derived altitudes.
(Hord, 1971)

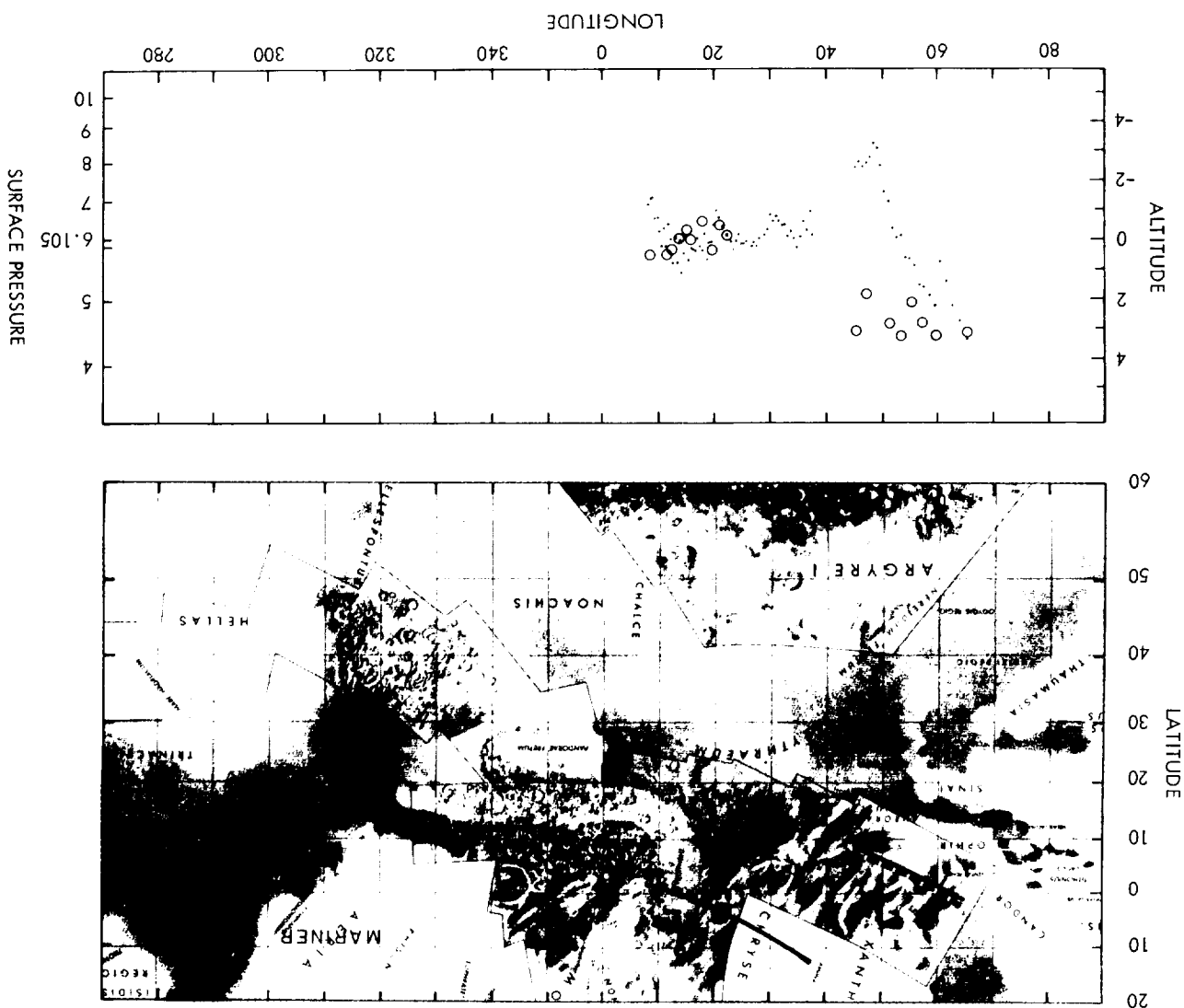
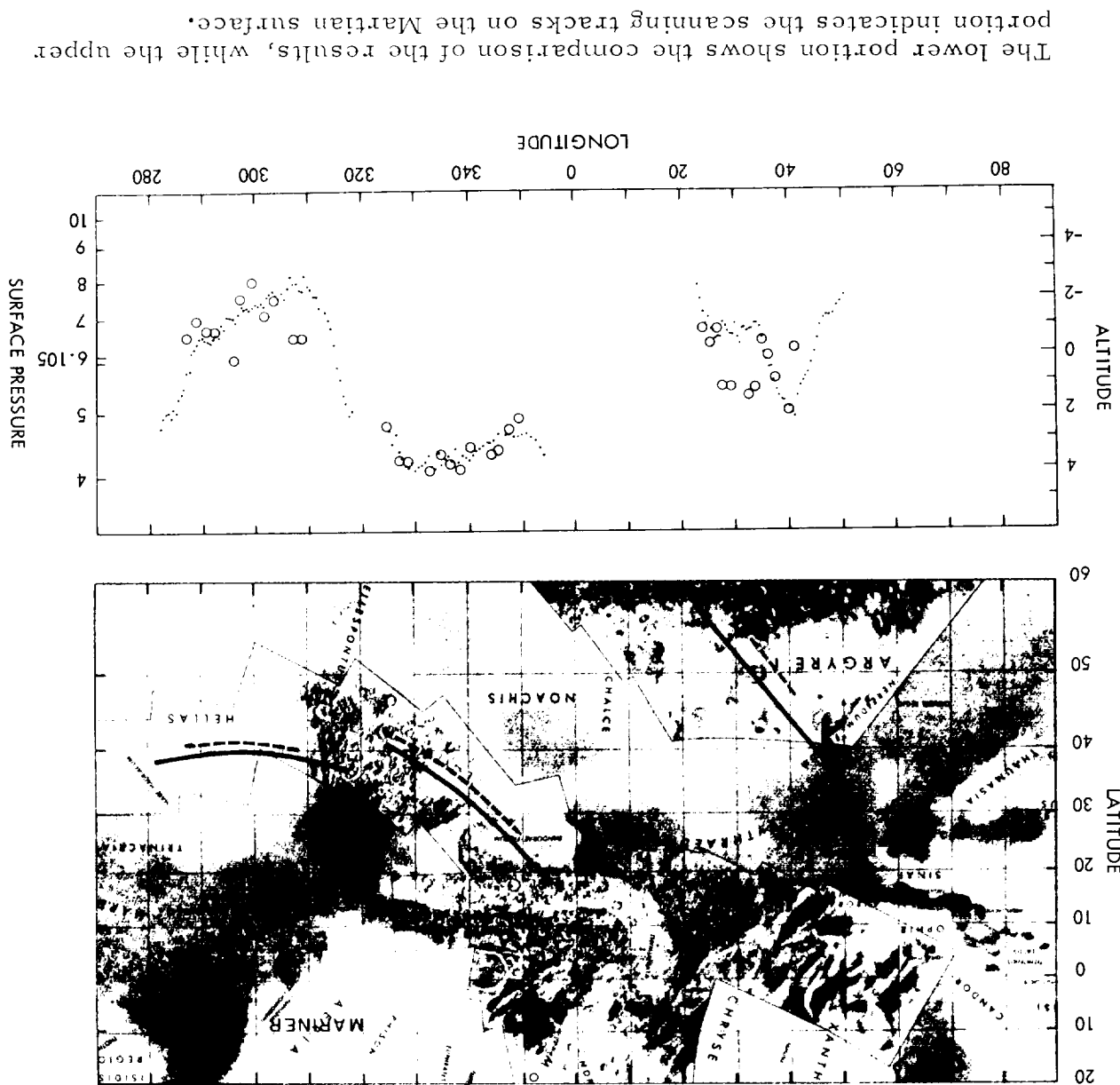


Fig. 3. Mariner 6 UVS and IRS surface pressures and derived altitudes. (Hord, 1971)

The lower portion shows the comparison of the results, while the upper portion indicates the scanning tracks on the Martian surface.

Fig. 2. Mariner 7 UVS and IRS surface pressures and derived altitudes. (Hord, 1971)



Margaritifer Sinus at its southwestern side, and Eos, are close to mean level (0 to 1 km) according to both UVS and IRS, but are definitely low (-3 to -4 km) according to the 1971 radar. This is again a major disagreement of 4 km.

Tip of Margaritifer Sinus and Aram channel are at mean level (0 km), according to both UVS and IRS; likewise, Thymiamata (UVS and IRS). But all this disagrees with the 1969 radar data showing a -2 and -3 km elevation.

2) From the 1967-1969 Radar Results

Contiguous deserts, Eden, Moab, and Arabia, appear to be at mean level. But Aeria and the western half of Syrtis Major are high ground (3 km, even 4 km), while the eastern half of Syrtis Major is a steep slope (3 km over 200 km), which, in fact, continues through Isidis Regio and especially in Moeris Lacus forms a hole 3 km deep. Amenthes is at mean level, but most of Aethiopsis is somewhat lower.

Elysium appears to be an isolated mountain, at least from its southern approaches or flank.

Complex Cerberus-Trivium Charontis is below mean level (-1 to -2 km), and southeast of it Mesogaea is a deep hole reaching -5 km. Amazonis likewise is low, but not as much (-3 to -4 km).

Nix Olympica, mostly low ground, sits on a fair slope climbing eastward from -4 to 1 km. Hougierius Lacus (east of Nix Olympica) is above Nix Olympica on this same large slope which reaches great heights of 6 km, where it meets Ascraeus Lacus to form one of the highest domes or uplifts on Mars, with summits at 7 or 8 km. Then there is an eastward downslope across Tractus Albus to Candor, which is apparently at zero level.

Lunae Palus has a high (2 km), and east of it are found markedly lower areas stretching as far as Thymiamata. Especially low is the part of Xanthe near Niliacus Lacus (-5 km) and the whole of Chryse (-3 km). Oxia Palus is at about -2 km.

3) From the 1971 Radar Results

Southern Aurorae Sinus (near Capri Cornu) has a deep gorge plunging to -6 km. Southern Margaritifer Sinus is quite low (-3 to -4 km). Then there is a steady rise eastward over Deucalionis Regio from -3 to 1 km in eastern Sabaeus Sinus. From Sabaeus Sinus to Mare Tyrrhenum, there is a long stretch of mean-level rolling plain (0 to -1 km). Iapygia and Trinacria are near zero level; then Aeolis and Zephyria have lows reaching -3 km.

Zephyria is quite low (-1 to -4 km), with depressions near Laestrygonum Sinus, apparently. Memnonia is generally low, but slopes up from -3 to 3 km going east. Then eastward this slope continues to rise steadily up to the highest summits (the "twin

peaks"), which may be part of the high uplifts previously mentioned. Phoenicis Lacus and the similarly shaped marking west of it (unnamed) are apparently at 6 and 7 km. Then eastward is a very gradual downslope to Sinai (Thaumasia) and Coprates, which are still high (2 km) however.

Radio occultation results of the three Mariner flybys have yielded values of "surface" pressure at six different locations on Mars (see Section 5.2, Table 1). The areas of northern Mare Acidalius, Electris, and Boreosyrtris, Hougaria are low regions. The tip of Meridiani Sinus is at average altitude, while southern Hellespontus is an elevated region. Cross-checking correlation with the above summary is possible only for the latter two or possibly three locations. Good agreement is noted.

Interpretation

For a small planet, Mars has a pronounced topography with altitude differences of at least 12 km. There are high elevations, plateaus, valleys, basins, ridges, gorges, etc., besides the many craters and ring-like structures. This implies that the structural (tectonic) development of Mars was rather complex and extensive, producing orogenetic uplifts and perhaps intrusive and extrusive magmatic activity (Binder, 1971). This supports the new concept of a differentiated Mars (see Section 2, Interior). It is interesting to note that some investigators (Leonardi, 1966; Katterfeld and Hedervari, 1969) of Mariner 4 pictures pointed out some striking resemblances in groups of craters and cirques on Mars, to eruptive and collapsed structures on Earth and presumably on the Moon.

3.5.2 NEW MARS MAPS

Several new maps and charts of Mars have been prepared since 1969. These maps and information concerning their source data and method of preparation are presented in the following sequence:

- 1) Mariner Mars 1969 Chart (NASA), including both polar regions.
- 2) International Planetary Patrol Photographic Maps of Mars 1969 and 1971 (Lowell Observatory).
- 3) Mariner Mars 1971 Planning Chart and Planning Charts of South Polar Regions (G. de Vaucouleurs).
- 4) Mariner Mars 1969 Photomap (J. Cutts, C.I. T.).
- 5) Mariner Mars 1969 Regional Maps (C. Cross).
 - a) Meridiani Sinus.
 - b) South Polar Region.

Mariner Mars 1969 Chart (NASA)

One of the most significant applications of the Mariner 1969 TV photography was the production of a much more reliable map of Mars, based for the first time on fixed topographic features (i. e., craters), and constructed according to modern photogrammetric principles. Accurate positioning of the Martian features was possible through a new areodetic control net established by Davies and Berg (1971) in cooperation with the Aeronautical Chart and Information Center (A. C. I. C.). This net consisted of 112 control points, or "clearly identifiable marks," on the surface of Mars. These control points were selected principally from crater centers, and when these were not available, the centers of particularly dark or light spots, or tips of markings, were used. Measurements of the positions of these control points on geometrically corrected FE and NE TV pictures permitted derivation of their Martian coordinates by analytical triangulation, knowing the position of the spacecraft and assuming a certain equatorial radius 3393.4 km) and polar flattening (21 km). The orientation of the coordinate system was determined by the direction of the rotational axis.

This new NASA Mars Chart 1969, Fig. 4, issued by the A. C. I. C. in August 1970, is a Mercator projection at the scale of 1:25,000,000 at the equator. In addition, there are two stereographic projections of the polar regions (60° to 90° latitude). The appearance of the main chart is quite striking when compared to earlier Mars charts, such as the MEC-2 produced in 1967 by the A. C. I. C. Besides the usual albedo mapping of dark and bright areas, it presents two large inserts corresponding to the equatorial and polar swaths covered, where topographic relief is qualitatively incorporated by air-brush renditions. Such interpretative renditions are of course subjective, depending upon the experience and judgment of the mapping staff guided only by visual inspection of the photographs. For example, the drawings in many places have tended to accentuate the relief.

The chart also includes the Mariner 4 (1965) swath from the equator to the south polar region, mostly across Mare Sirenum and Phaetontis.

The albedo mapping is that obtained from the July-August 1969 encounter period. The traditional permanent dark and light areas are easily recognizable and some secular changes are noticeable to those familiar with Mars, but no seasonal changes were yet manifested at the time.

The basic nomenclature, or list of areographical names, is that adopted by the 1958 IAU Congress. However, additional well-known names are used where needed.

The longitude system is the standard westward-counting 0 to 360 degree system long used by areographers and telescopic observers of Mars.

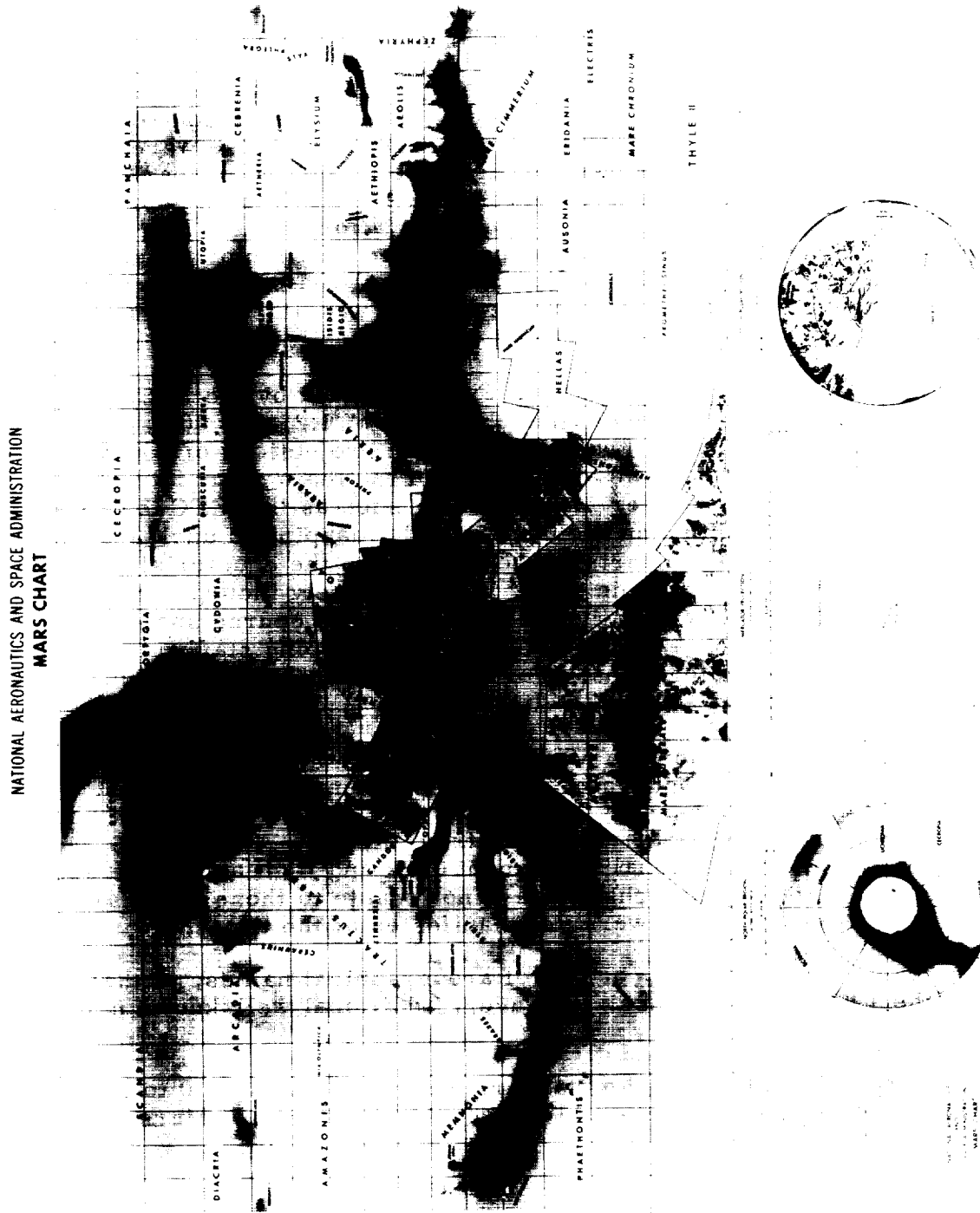


Fig. 4. NASA Mars Chart 1969.

International Planetary Patrol Photographic Maps of Mars 1969 and 1971 (Lowell Observatory)

Mars 1969

This new albedo map of the Mars 1969 apparition was prepared at Lowell Observatory's Planetary Research Center, from thousands of photographs taken with identical photographic equipment (camera systems and focal lengths, filters). The photos were obtained under the control of the International Planetary Patrol Program, by a network of six observatories located around the Earth. The participating observatories were Lowell Observatory, Flagstaff, Arizona (Coordinating Center); Maunaea Kea Observatory in Hawaii; Cerro Tololo Inter-American Observatory, Chile; Mount Stromlo Observatory, Australia; Republic Observatory, Johannesburg, South Africa; and the Magdalena Peak Station of New Mexico State University, New Mexico. The photographic period of a month and a half transpired between May 19 and July 19, 1969 (opposition date, May 31). Although filters in all colors were used, only the red filter* photographs were selected for the mapping to obtain maximum contrast of Mars surface features. Areographic positions were obtained on the images by superimposing the appropriate orthographic graticule of latitude-longitude lines, through a specially built projection image reader. Mean positional error was estimated to be less than a degree for latitudes between 40°N and 30°S. The new Mercator map is shown in Fig. 5 and contains the names of 191 Martian features properly inscribed so as to form a key map. The list of names adopted comprises 113 names from the Standard IAU 1958 List, plus a selection of traditional names most widely used today. Both the key map and the list of names, which included the approximate 1969 location coordinates, are shown in Table 1. The objectivity of the cartographic procedures employed by the authors (Inge et al., 1971) of this Earth-based telescopic map undoubtedly provided a high level of reliability. In their own words, "Our cartography was carried out completely 'de novo,' without the use of earlier maps or earlier notions concerning the nature of various markings. Care was taken not to over-interpret the photographic evidence."

Mars 1971

A similar photographic map for the 1971 apparition (Fig. 6) was prepared, using the same techniques. The same observatories participated (in supplying the red filter photos), with the exception of Magdalena Peak Observatory, and the addition of Perth Observatory, Western Australia, and Kavalur Observatory, Indian Institute of Astrophysics, India. Resolution was a little better since Mars was closer in 1971, especially for the Southern Hemisphere turned toward Earth.

Mariner Mars 1971 Planning Charts

An albedo map of Mars as it is expected to appear about January 1, 1972 -- the time of the Mariner 1971 orbital mission -- was prepared by G. de Vaucouleurs (1971) with the aid of J. Roth, artist. At this time, Mars

*Red filter passband 300 Å wide, centered on $\lambda 6200$ Å.

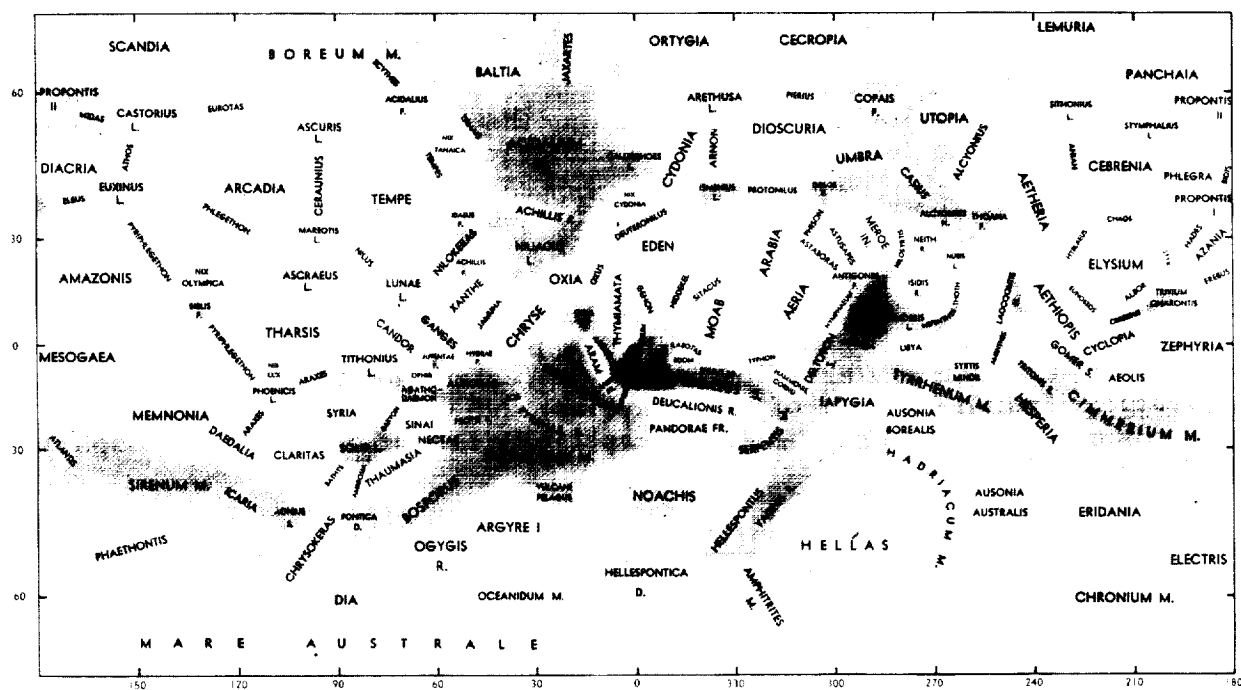
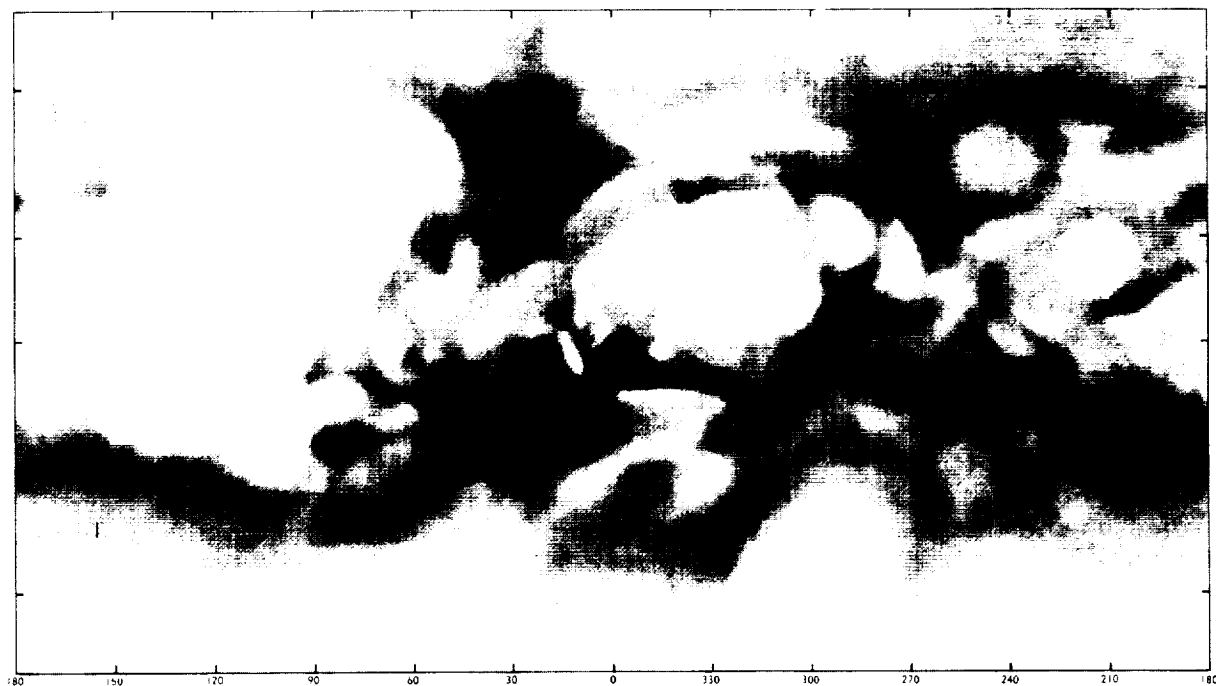


Fig. 5. 1969 Mars Patrol Photographic Map (Lowell Observatory)
(Inge et al., 1971).

Table 1. List of names used on the International Planetary Patrol
Photographic Map of Mars 1969 (Lowell Observatory)*

1. <i>Achillis Fons</i> , 53°, +23°	66. Deucalionis Regio, 345°, -18°	131. Nix Olympica, 132°, +21°
2. <i>Achillis Pons</i> , 30°, +37°	67. Deuteronilus, 358°, +35°	132. Nix Tanaica, 55°, +52°
3. Acidalium Mare, 28°, +48°	68. <i>Dia</i> , 88°, -60°	133. Noachis, 355°, -40°
4. <i>Acidalius Fons</i> , 63°, +58°	69. Diacria, 170°, +47°	134. Nubis Lacus, 264°, +24°
5. Aeolis, 212°, -10°	70. Dioscuria, 315°, +54°	135. <i>Nymphaeum</i> , 300°, +10°
6. Aeria, 310°, +15°	71. <i>Eden</i> , 350°, +28°	136. <i>Oceanidum Mare</i> , 35°, -60°
7. Aetheria, 240°, +40°	72. Edom, 345°, -4°	137. Ogygis Regio, 60°, -53°
8. Aethiopia, 235°, +10°	73. Electris, 190°, -52°	138. Ophir, 65°, -10°
9. <i>Agathodacnion</i> , 65°, -14°	74. <i>Eleus</i> , 168°, +40°	139. Ortygia, 350°, +65°
10. <i>Albor</i> , 208°, +18°	75. Elysium, 215°, +25°	140. <i>Oxia</i> , 20°, +20°
11. <i>Alcyonius Nodus</i> , 268°, +35°	76. <i>Eos</i> , 37°, -15°	141. <i>Oxia Palus</i> , 17°, +8°
12. <i>Alcyonius</i> , 260°, +50°	77. <i>Erebus</i> , 182°, +20°	142. Oxus, 12°, +20°
13. Amazonis, 160°, +20°	78. Eridania, 218°, -45°	143. Panchaia, 205°, +62°
14. <i>Ambrosia</i> , 85°, -38°	79. Erythraeum Mare, 30°, -30°	144. Pandorae Fretum, 345°, -25°
15. Amenthes, 251°, +3°	80. Eunostos, 225°, +15°	145. Phaethontis, 150°, -50°
16. <i>Amphitrites Mare</i> , 322°, -58°	81. <i>Eurotas</i> , 125°, +58°	146. Phison, 308°, +35°
17. <i>Anian</i> , 228°, +48°	82. <i>Euxinus Lacus</i> , 155°, +43°	147. <i>Phlegethon</i> , 125°, +35°
18. <i>Antigones Fons</i> , 295°, +20°	83. <i>Fastigium Aryn</i> , 358°, 0°	148. <i>Phlegra</i> , 190°, +45°
19. <i>Aonius Sinus</i> , 105°, -47°	84. <i>Ganges</i> , 60°, +5°	149. Phoenicis Lacus, 110°, -15°
20. Arabia, 320°, +28°	85. Gehon, 358°, +15°	150. <i>Pierius</i> , 310°, +59°
21. <i>Aram</i> , 12°, -5°	86. Geryon, 75°, -22°	151. <i>Pontica Depressio</i> , 85°, -47°
22. Araxes, 117°, -24°	87. <i>Gomer Sinus</i> , 230°, -2°	152. Propontis I, 180°, +40°
23. Arcadia, 115°, +42°	88. <i>Hades</i> , 192°, +33°	153. Propontis II, 179°, +58°
24. <i>Arethusa Lacus</i> , 337°, +58°	89. Hadriacum Mare, 270°, -40°	154. Protei Regio, 50°, -22°
25. <i>Argus</i> , 10°, 0°	90. <i>Hammonis Cornu</i> , 316°, -13°	155. Protonilus, 320°, +42°
26. Argyre I, 35°, -48°	91. Hellas, 295°, -50°	156. <i>Pyrriphlegethon</i> , 140°, +20°
27. Arnon, 337°, +50°	92. Hellespontica Depressio, 358°, -58°	157. Pyrrhae Regio, 30°, -22°
28. <i>Asdraeus Lacus</i> , 100°, +20°	93. Hellespontus, 330°, -47°	158. Sabaeus Sinus, 335°, -12°
29. <i>Ascuris Lacus</i> , 95°, +53°	94. Hesperia, 240°, -20°	159. Scandia, 150°, +66°
30. <i>Astaboras</i> , 305°, +26°	95. Hiddekel, 347°, +18°	160. <i>Scythes</i> , 75°, +64°
31. <i>Astusapes</i> , 298°, +30°	96. <i>Hyblaeus</i> , 228°, +30°	161. Serpentis Mare, 320°, -28°
32. <i>Athos</i> , 153°, +48°	97. <i>Hydrae Pons</i> , 48°, -3°	162. <i>Sigeus Portus</i> , 335°, -8°
33. <i>Atlantis</i> , 173°, -30°	98. <i>Iani Fretum</i> , 10°, -10°	163. Sinai, 65°, -23°
34. Aurorae Sinus, 50°, -13°	99. Iapygia, 295°, -15°	164. Sirenum Mare, 140°, -40°
35. Ausonia Australis, 250°, -40°	100. Icaria, 124°, -45°	165. <i>Sitacus</i> , 338°, +17°
36. <i>Ausonia Borealis</i> , 275°, -23°	101. <i>Idaeus Fons</i> , 53°, +35°	166. Sithonius Lacus, 230°, +58°
37. Australe Mare, 90°, -65°	102. Isidis Regio, 275°, +20°	167. Solis Lacus, 85°, -30°
38. <i>Azania</i> , 185°, +30°	103. Ismenius Lacus, 335°, +42°	168. <i>Stymphalius Lacus</i> , 205°, +54°
39. Baltia, 40°, +63°	104. <i>Jamuna</i> , 44°, +10°	169. Styx, 200°, +25°
40. <i>Bathys</i> , 92°, -38°	105. Jaxartes, 22°, +65°	170. Syria, 90°, -20°
41. <i>Biblis Fons</i> , 132°, +10°	106. Juventae Fons, 62°, -4°	171. Syrtis Major, 290°, +10°
42. <i>Bidis</i> , 182°, +45°	107. <i>Labotas</i> , 345°, 0°	172. Syrtis Minor, 260°, -8°
43. Boreum Mare, 95°, +65°	108. <i>Laocoontis Nodus</i> , 246°, +15°	173. Tanais, 50°, +55°
44. <i>Bosporus Gemmatus</i> , 63°, -43°	109. Lemuria, 230°, +70°	174. Tempe, 75°, +40°
45. <i>Callirrhoe Sinus</i> , 3°, +50°	110. Libya, 275°, 0°	175. <i>Tempes</i> , 63°, +47°
46. Candor, 75°, +5°	111. Lunae Lacus, 71°, +15°	176. <i>Tharsis</i> , 103°, +8°
47. Casius, 275°, +43°	112. <i>Mareotis Lacus</i> , 96°, +32°	177. Thaumasia, 75°, -35°
48. <i>Castorius Lacus</i> , 150°, +55°	113. Margaritifer Sinus, 20°, -10°	178. <i>Thoana Palus</i> , 256°, +35°
49. Cebrenia, 215°, +48°	114. Memnonia, 142°, -20°	179. Thoth, 263°, +15°
50. Cecropia Mare, 305°, +67°	115. Meridiani Sinus, 0°, -5°	180. Thymiamata, 6°, +10°
51. Ceraunius, 96°, +42°	116. <i>Meroe Insula</i> , 290°, +30°	181. Tithonius Lacus, 80°, -5°
52. Cerberus, 212°, +9°	117. <i>Mesogaea</i> , 168°, -2°	182. <i>Tritonis Sinus</i> , 240°, -10°
53. <i>Chaos</i> , 215°, +35°	118. <i>Midas</i> , 165°, +56°	183. Trivium Charontis, 198°, +14°
54. Chronium Mare, 215°, -60°	119. Moab, 338°, +10°	184. <i>Typhon</i> , 322°, -4°
55. Chryse, 32°, +8°	120. Moeris Lacus, 278°, +8°	185. Tyrrhenum Mare, 270°, -13°
56. Chrysokeras, 100°, -52°	121. Nectar, 60°, -28°	186. Umbra, 290°, +49°
57. Cimmerium Mare, 210°, -25°	122. Neith Regio, 275°, +30°	187. Utopia, 265°, +56°
58. Claritas, 102°, -30°	123. Nepenthes, 268°, +8°	188. Vulcani Pelagus, 25°, -40°
59. <i>Coloe Palus</i> , 304°, +43°	124. <i>Neudrus</i> , 4°, -15°	189. Xanthe, 50°, +15°
60. Copais Palus, 288°, +58°	125. Niliacus Lacus, 32°, +27°	190. Yaonis Regio, 318°, -43°
61. <i>Crocea</i> , 293°, 0°	126. Nilokeras, 55°, +28°	191. Zephyria, 190°, 0°
62. Cyclopa, 218°, 0°	127. Nilosyrtis, 280°, +30°	
63. Cydonia, 345°, +50°	128. <i>Nilus</i> , 82°, +25°	
64. <i>Daedalia</i> , 120°, -34°	129. Nix Cydonia, 3°, +40°	
65. <i>Deltoton Sinus</i> , 304°, -5°	130. Nix Lux, 110°, -7°	

*Italics indicate names not used on the International Astronomical Union's 1958 map of Mars

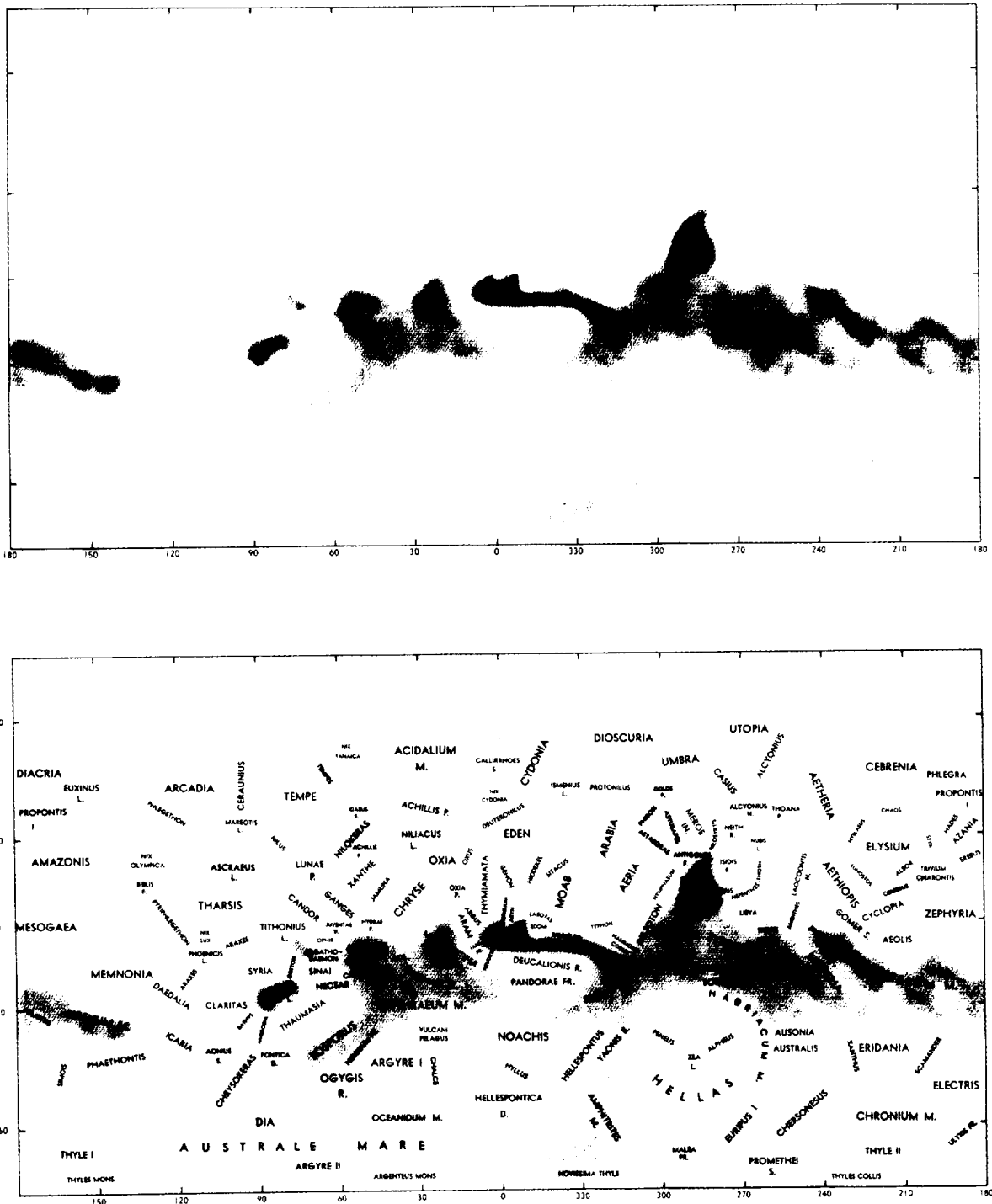


Fig. 6. 1971 Mars Patrol Photographic Map (Lowell Observatory)

will be experiencing midsummer in its Southern Hemisphere. The heliocentric orbital longitude of Mars will be $\eta = 45^\circ$, or the areocentric longitude of the Sun: $L_S = 320^\circ$. This "planning chart" includes only the relatively stable features as they appeared in 1941 and 1958, at nearly the same η for Mars, plus updating for the most recently observed secular changes (1969 observations by both Mariner FE sequences, and by Earth observatories). The 1971 perihelic opposition is to provide further updating data for later versions of the basic chart.*

The basic cartographic information--the areodetic net employed--was produced by G. de Vaucouleurs (1965, 1969) for his Mars Map Project, begun in 1958 at Harvard Observatory and completed at the University of Texas in 1969. The basic data is derived from hundreds of both visual observations, since the time of Schiaparelli (1877), and photographic observations, begun in 1924. This should ensure the reliability of the control stations (79 altogether). Preliminary comparisons with the NASA Mars Chart 1970 indicate agreement within $\pm 2^\circ$, in both coordinates.

The resolution limit on this Mercator chart is on the order of 50 to 150 km (i.e., 1° to 3° areographic), depending upon the degree and gradient of brightness contrast and quality of the basic photographic data. No attempt was made to include the topographic details (craters, etc.) seen in the NE frames of Mariners 6 and 7 or the FE frame fine structure observed in the Tharsis region.

The nomenclature is basically that of Antoniadi (1930), with some revisions and additions recommended by the IAU in 1958, or required by recent surface changes.

The planning chart is shown in Fig. 7. The list of names identified on the planning chart is shown in Table 2.

Charts for the South Polar Region and Cap

To supplement their 1971 Planning Chart, the authors later issued (November 1971) two orthographic projection charts of the South Polar Region (Fig. 8), showing the cap at two different stages of regression, as follows: One chart of this region shows nearly all bare ground, with only a very small (7° across) eccentric residual cap close to the pole, as it appears in Southern midsummer when $L_S = 320^\circ$. The other chart represents the same region overlaid by the expanded polar cap of midspring when $L_S = 220^\circ$, and actively regressing; it displays the well-known (recurring every Martian year) pattern of rifts ("rima"), brilliant patches ("mons"), and dark patches ("depressio").

Observations used for the $L_S = 320^\circ$ chart dated from 1941 and 1958, especially, with others since 1877. Observations used for the $L_S = 220^\circ$ chart were made at the perihelic oppositions of 1909, 1924, and 1971.

*An updated version containing 1971 opposition information up to September 17, 1971 has already appeared.

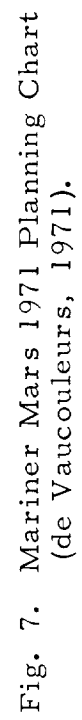
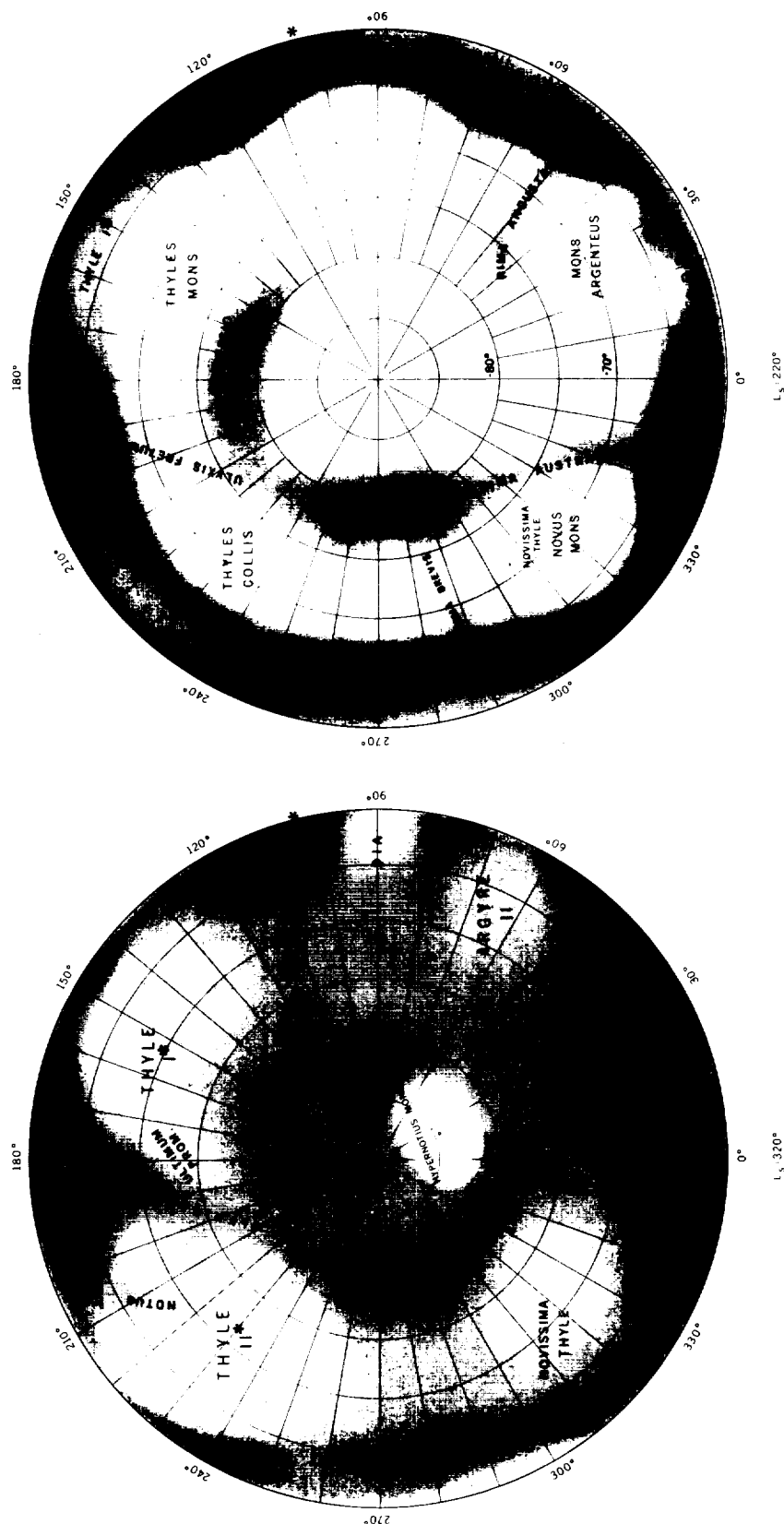


Table 2. List of names used on the Mariner Mars 1971 Planning Chart (de Vaucouleurs, 1971).

1 Acidalium, Mare	30 +48	50 Edom	345 -03	100 Oxia	18 +20
2 Achilles Pons	30 +38	51 Electris	180 -48	101 Oxia Palus	17 +10
3 Aeolis	210 -05	52 Elysium	215 +23	102 Palinuri Fretum	145 -60
4 Aeria	310 +15	53 Eos	37 -15	103 Pandora Fretum	345 -25
5 Aetheria	240 +35	54 Eridania	218 -45	104 Pavonis Lacus	114 0
6 Aethiopsis	235 +05	55 Euxinus Lacus	157 +43	105 Phaethontis	140 -48
7 Alba	106 +45	56 Erythraeum, Mare	30 -33	106 Phlegra	190 +30
8 Amazonis	150 +03	57 Ganges	60 +05	107 Phoenicis Lacus	108 -15
9 Amenethes	255 +15	58 Gehon	357 +16	108 Promethei Sinus	260 -62
10 Aonius Sinus	115 -50	59 Gomer Sinus	225 -05	109 Propontis I	182 +43
11 Arabia	325 +20	60 Gorgonum Sinus	149 -30	110 Propontis II	177 +55
12 Aram	13 -05	61 Hadriacum, Mare	278 -35	111 Protonilus	318 +42
13 Arcadia	120 +45	62 Hellas	294 -47	112 Pyrrhae Regio	20 -25
14 Argyre I	30 -46	63 Hellespontica		113 Rasena	192 -26
15 Argyre II	72 -65	Depressio	345 -62	114 Sabaeus Sinus	330 -10
16 Ascræus Lacus	100 +18	64 Hellespontus	323 -40	115 Scamander	197 -48
17 Atlantis	168 -30	65 Herculis Pons	180 +50	116 Serpentis, Mare	320 -25
18 Auroræ Sinus	50 -14	66 Hesperia	240 -20	117 Simois	160 -48
19 Ausonia	250 -40	67 Hougéria	144 +25	118 Sinai	75 -20
20 Australe, Mare	25 -60	68 Hougierius Lacus	130 +20	119 Sirenum, Mare	155 -32
21 Bosphoros	75 -40	69 Iapygia	298 -15	120 Sirenum Sinus	130 -35
22 Candor	70 0	70 Icaria	123 -40	121 Solis Lacus	85 -27
23 Capri Cornu	50 -20	71 Idacus Fons	53 +30	122 Styx	202 +28
24 Caralis Fons	155 -42	72 Isidis Regio	275 +20	123 Syria	98 -20
25 Casius	265 +42	73 Ismenius Lacus	333 +40	124 Syrtis Major	290 +12
26 Castorius Lacus	155 +53	74 Juventae Fons	62 -05	125 Syrtis Minor	260 -10
27 Cebrenia	215 +45	75 Laestrygonum Sinus	198 -20	126 Tempe	68 +45
28 Ceraunius	95 +25	76 Libya	272 -01	127 Thaumasia	82 -38
29 Cerberus	208 +10	77 Lunae Palus	65 +20	128 Tharsis	105 -03
30 Chersonesus	260 -53	78 Margaritifer Sinus	23 -10	129 Thyle I	150 -67
31 Chronium, Mare	180 -60	79 Melas Lacus	73 -13	130 Thyle II	225 -67
32 Chryse	35 +10	80 Memnonia	148 -20	131 Thymiamata	5 +15
33 Chrysokeras	98 -55	81 Meridiani Sinus	358 -05	132 Tiphys Fretum	220 -57
34 Cimmerium, Mare	210 -30	82 Meroe	290 +32	133 Titanum Sinus	168 -20
35 Claritas	102 -32	83 Mesogaea	170 0	134 Tithonius Lacus	83 -03
36 Coloe Palus	299 +44	84 Moab	340 +20	135 Tractus Albus	
37 Copais Palus	275 +56	85 Moeris Lacus	270 +08	(Australis)	95 0
38 Coprates	65 -15	86 Nectar	67 -28	136 Tractus Albus	
39 Crocea	285 -05	87 Neith Regio	272 +35	(Borealis)	75 +28
40 Cyclopum Sinus	226 -08	88 Nepenthes	265 +15	137 Trinacria	275 -25
41 Cydonia	355 +45	89 Nereidum Fretum	55 -45	138 Tritonis Sinus	245 -06
42 Daedalia	118 -27	90 Niliacus Lacus	32 +32	139 Trivium Charontis	200 +15
43 Deltoton Sinus	305 -07	91 Nilokeras	58 +34	140 Tyrrhenum, Mare	255 -22
44 Deucalionis Regio	345 -17	92 Nilosyrtis	280 +43	141 Umbra	285 +50
45 Deuteronilus	357 +35	93 Nix Olympica	138 +20	142 Utopia	245 +52
46 Dia	85 -60	94 Noachis	350 -45	143 Xanthe	52 +12
47 Diacria	163 +48	95 Noctis Lacus	94 -10	144 Yaonis Fretum	310 -35
48 Dioscuria	318 +48	96 Nodus Gordii	130 -05	145 Yaonis Regio	315 -33
49 Eden	350 +20	97 Oenotria	298 -02	146 Zea Lacus	290 -47
		98 Ogygis Regio	63 -42	147 Zephyria	182 -10
		99 Ophir	65 -10		



ORTHOGRAPHIC PROJECTION
Scale = 1:25,000,000 at the center of the grid.

Radius of planet = 3394 km from ground-based radar and Mariner IV values (ellipticity of globe neglected).

Fig. 8. Mariner Mars 1971 Planning Charts of South Polar Regions
(G. de Vaucouleurs).

Mariner Mars 1969 (J. Cutts)

A photomap of Mars, Fig. 9, assembled from Mercator projection sections of the Mariner 6 and 7 FE pictures and obtained by a special computer program (GEOM), transforming a quadrilateral into a rectangle, was produced in the JPL Image Processing Laboratory, using the technique described by Rindfleisch et al. (1971).^{*} The photomap accurately provides, with no subjective interpretations, the appearances and positions of the Martian surface features at the time of photography (end of July-early August 1969), for latitudes between 50°N and 70°S. The areodetic positions were established from the Davies and Berg (1971) control net for Mars. When first assembling the Mercator sections, a problem was encountered due to a sharp discontinuity in brightness between edges of segments, caused by differences in solar illumination and viewing angle. By using an appropriate photometric function (Minnaert's model, see Section 3.2 on Photometric Properties), it was possible to obtain matching of the sections. This was done by selecting parameter k in Minnaert's photometric function $B/B_0 = (\cos i)^k (\cos e)^{k-1}$, as $k = 0.6$.

The photomap of Mars is illustrated in Fig. 9, including a diagram of the GEOM transformation scheme used by Cutts et al. (1971).

Mariner Mars 1969 Meridiani Sinus Region Map (C. Cross)

Cross (1971a) has produced a map of the Meridiani Sinus region (see Fig. 10), which incorporates both the albedo and the topography information from the Mariner 6 and 7 TV pictures. He used the fine detail revealed by the "Max-D" versions, as well as the true-intensity contrasts provided by the "photometric" versions of the NE pictures. The overall albedos were adjusted to match those of the FE pictures. The result was a "compromise" map blending the two aspects. The terrain features were rendered by an artist's charcoal-and-stump technique. The positional accuracy of the feature locations and orientations were assured by transferring these from the NASA Mariner Mars 1969 Chart, using the available control points of the areodetic net of Davies and Berg (1971).

The northern and southern border regions of Fig. 10 are drawn only from the FE pictures and indicate a near-absence of craters. Solar elevation is near zenithal for the western edge of the chart, where there are no shadows, and about 75° from zenith toward the eastern edge (near 350°W), where shadows become pronounced.

Of particular interest are the dark highland promontory at the northern tip of Margaritifer Sinus (near 17°W), the area of chaotic terrain (centered at 35°W) with channels extending into both Margaritifer Sinus and Chryse, and the very large craters (300 and 225 km) in Edom and Deucalionis Regio.

^{*}A similar computer photomap of Mars, but at much higher resolution (obtained by using a much finer grid system) is presently under preparation by R. B. Leighton of C.I.T.

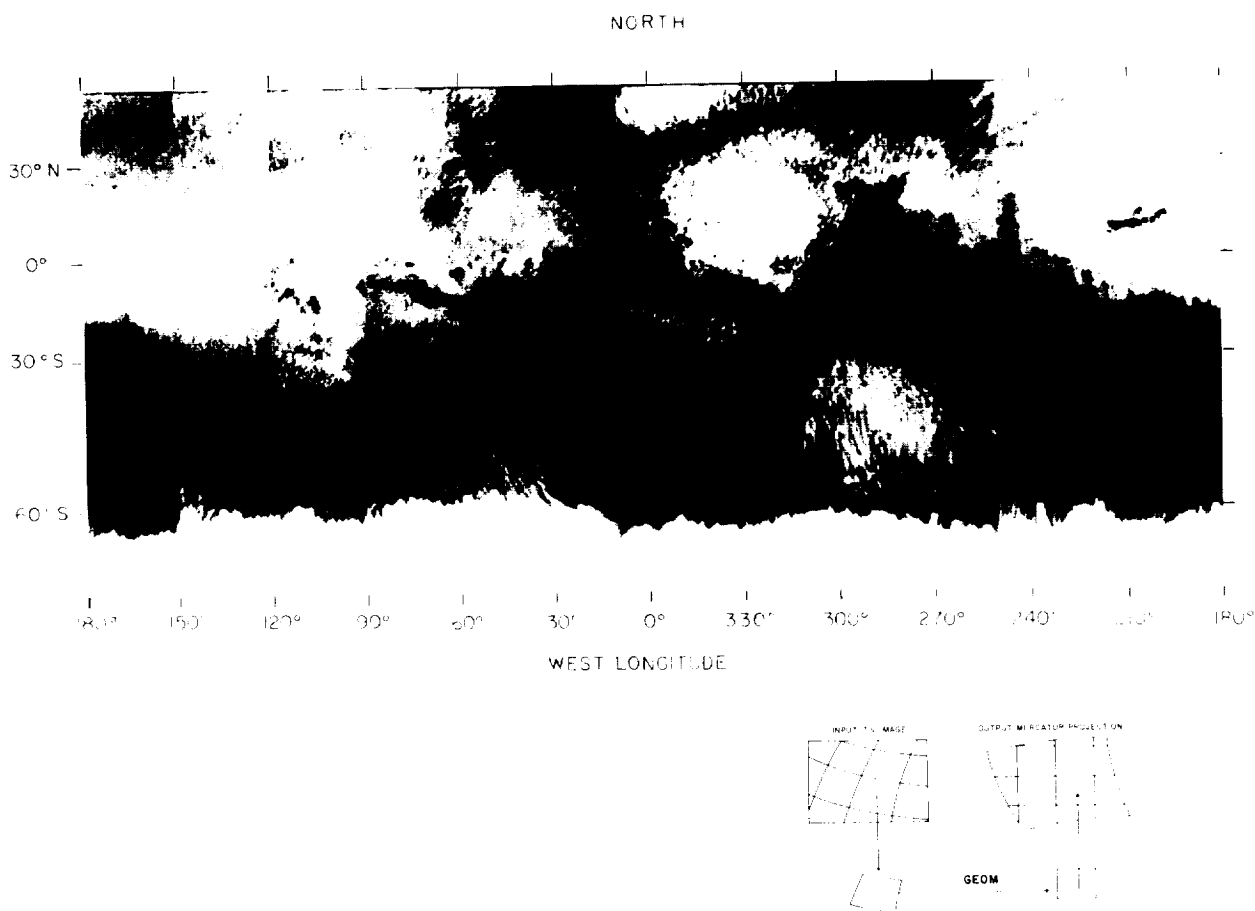


Fig. 9. Mariner Mars 1969 Photomap (J. Cutts).

Mariner Mars 1969 South Polar Region Map (C. Cross)

Cross (1971b) also prepared a stereographic projection chart of the portion of the South Polar Region and Cap photographed by Mariner 7, Fig. 11. Again he combined albedo and topography, using the same charcoal rendering technique. Positioning of features was based upon the areodetic control points for the South Polar Region used in making the NASA Mariner Mars 1969 polar chart.

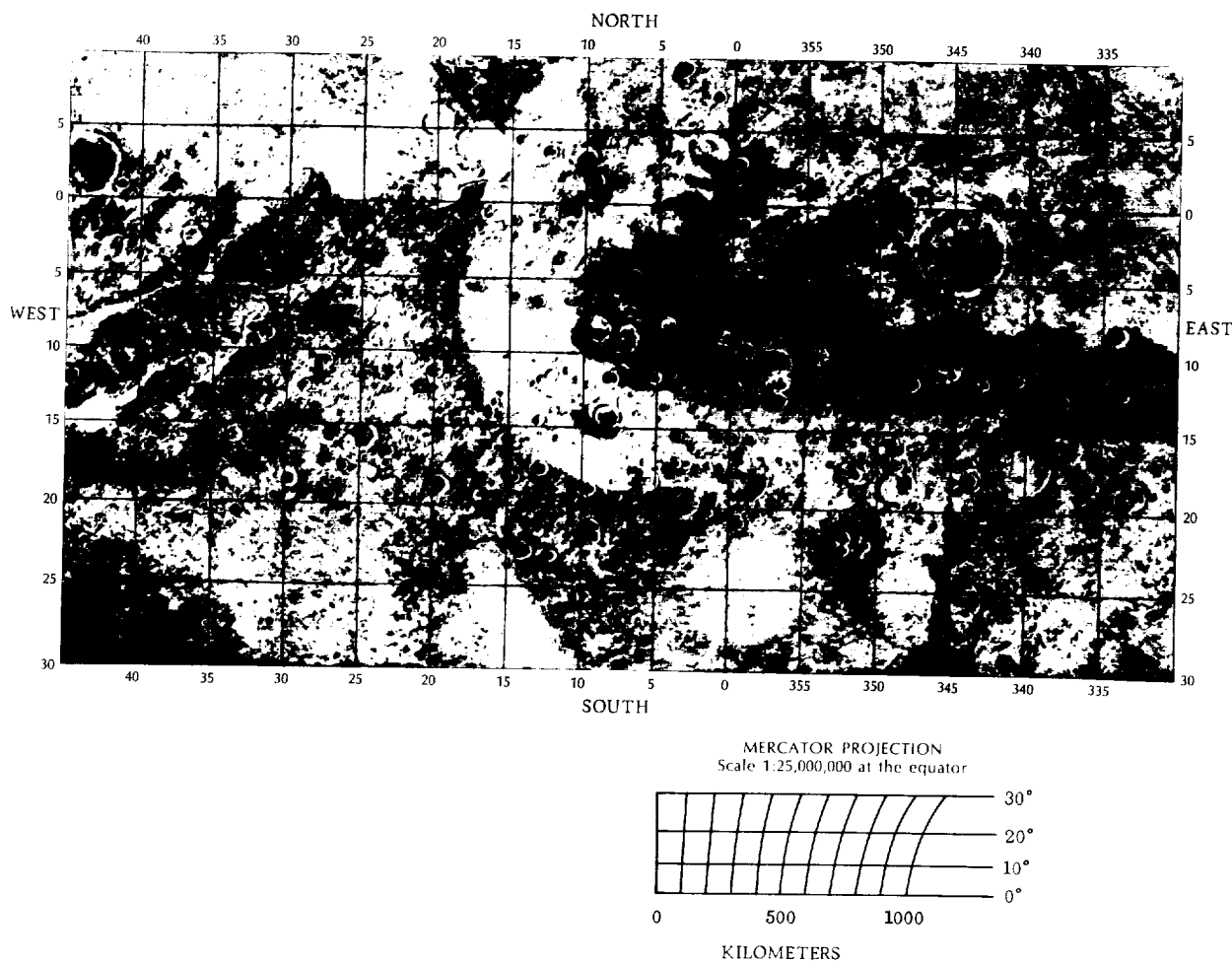


Fig. 10. Mariner Mars 1969 Meridiani Sinus Region Map (C. Cross).

3.5.3 TYPES OF TERRAINS

Cratered Terrain

Mariner 4 Photography*

In 1965, Mariner 4 discovered heavily cratered terrain on Mars. The most striking morphological features seen on the photographs were these numerous craters of smooth and subdued appearance, ranging in size from

*See Fig. 24 (Section 3.5) from the first edition (1968) of this document, which shows Mariner 4 pictures 7-12. The complete set of 22 pictures was presented and fully documented in the final report by Leighton et al., 1967.

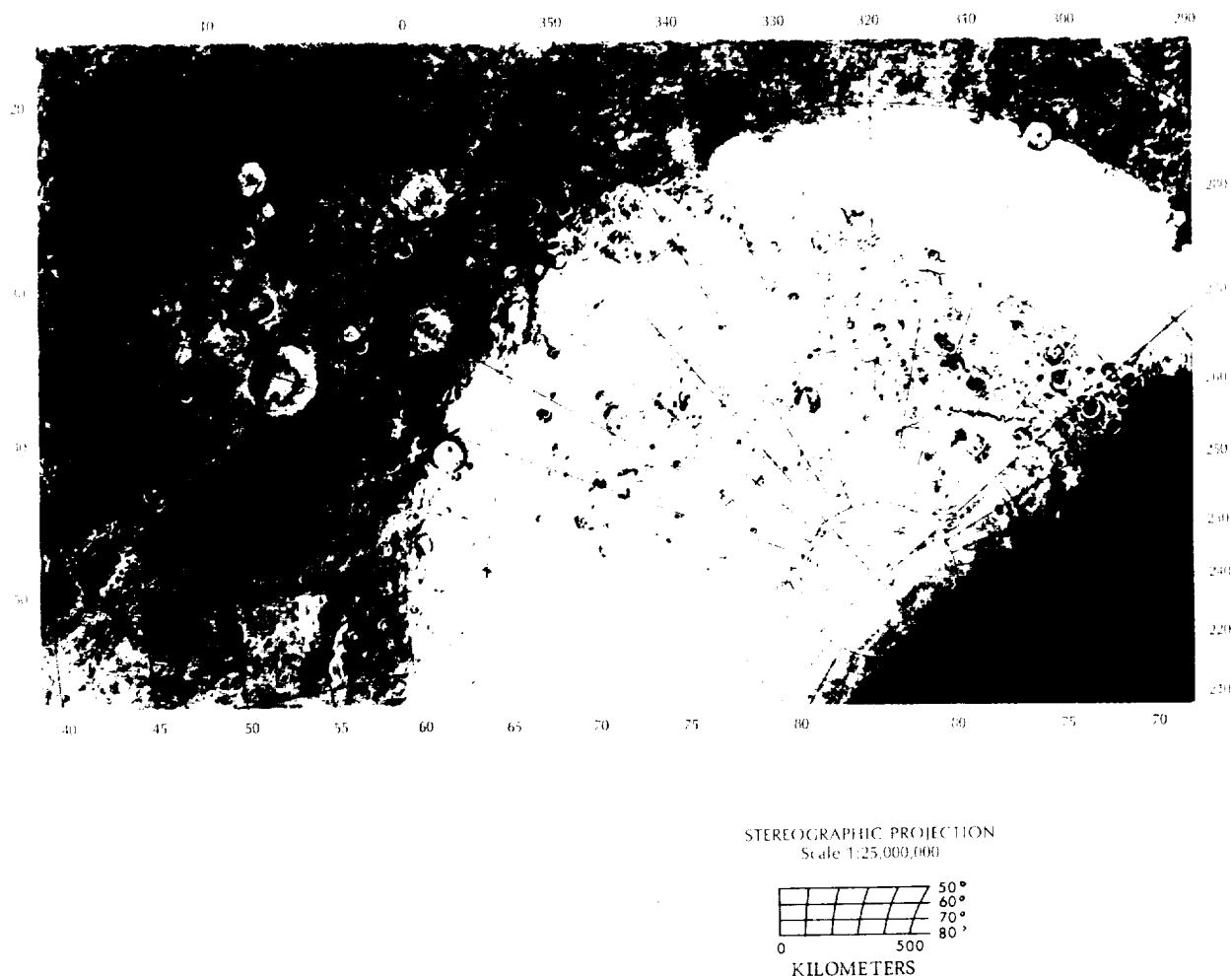


Fig. 11. Mariner Mars 1969 South Polar Region Map (C. Cross).

the limit of available resolution (3 km) up to at least 180 km. Over 600 definite and possible craters were counted in Mariner 4 frames 4N3-16.* The craters were classified--rather subjectively--according to three categories, based on degree of preservation: well-preserved, of intermediate preservation, and poorly preserved. Table 3 gives a summary of the compilation by the principal investigators (Leighton et al., 1967), for successive picture pairs. The table includes the diameters of the smallest and largest craters, as well as the number of craters displaying central peaks and polygonal outlines. It is seen that the percentage of well-preserved craters is not high (14%), and that they are more abundant in pictures 4N7-14, located, in most part, across the

*Picture designation conforms to that used for Mariners 6 and 7 explained in Section 3.6, Photographic Atlas.

Table 3. Summary compilation of Martian crater data from Mariner 4 pictures 4N3-16 (Leighton et al., 1967).

Pictures	Total number	Central peaks	Polygonal outline	Smallest dia., km	Largest dia., km	Well preserved	Intermediate preservation	Poorly preserved
3, 4	88	1	0	6	80	5	37	46
5, 6	92	6	2	5	64	9	40	43
7, 8	115	7	10	4	180	18	45	52
9, 10	132	11	10	4	123	19	64	49
11, 12	97	8	9	3	175	20	42	35
13, 14	67	4	4	5	350(?)	12	19	36
15, 16	45	2	3	7	114	3	22	20
	636	39	38	Smallest 3 km	Largest 350(?) km	86	269	281

Mare Sirenum-Mare Cimmerium complex. Only two craters of 3-km size were counted, while a very large one (350 km) seemed present (its rim appears on 4N13). About 6% of the craters displayed polygonal outlines or central peaks. Few display both characteristics. The numbers given are considered somewhat uncertain, however, since crater recognition and classification on the Mariner 4 pictures is difficult, mainly due to the limited intensity discriminability of the imaging system and the poor photographic rendition under the unfavorable high-Sun illumination conditions, which created little if any shadow in the best pictures (4N7-12). Recognition of craters in the 3-4 km size range was especially difficult.

Mariner 4 Crater Statistics and Analyses

Leighton et al. (1967) Analysis. The cumulative size-frequency distribution of craters recognized in 4N7-12 was plotted, with subdivision into "definite," "probable," and "possible" categories, reflecting degree of rim preservation (see Fig. 12). This plot shows for the 20-60 km sizes, or above, a curve slope approximating that for the lunar upland craters and an absolute abundance only slightly lower. For sizes under 20 km, the Mars curve flattens out to lower frequencies. This bend, indicating a deficiency in small crater abundance, may be considered real (as did Leighton et al., 1967), and interpreted as due to crater modification processes (erosion and deposition), which become more effective on smaller craters; or it may be considered suspect (as did Chapman et al., 1969) and attributed in large part to observational incompleteness in the crater counts. In any case, the Martian craters, whether all counted or not, generally appear much more eroded than those of the lunar uplands.

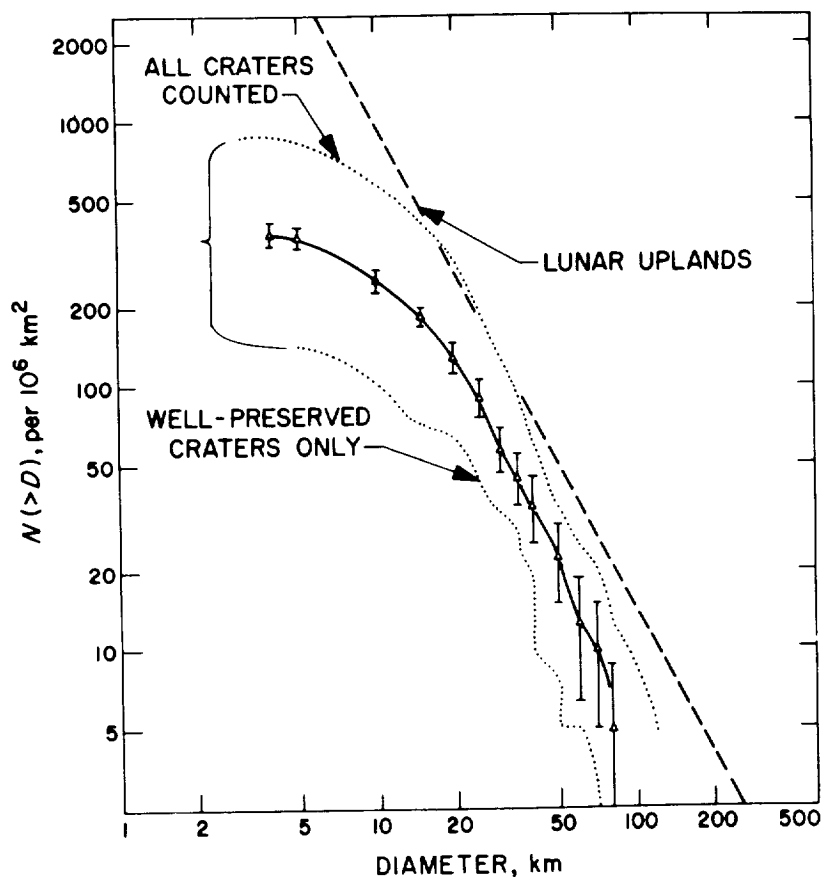


Fig. 12. Cumulative size-frequency distribution of craters recognized in Mariner 4 pictures 4N7-12 (Leighton et al., 1967).

Other observations made by the investigators from picture examination were as follows:

- 1) Central peaks and polygonal outlines were associated mostly with the relatively well-preserved craters.
- 2) Well-preserved craters are more abundant in the small and medium sizes, while many of the larger craters are faint.
- 3) Polygonalization was more abundant in intermediate-size craters (15-45 km).
- 4) Irregular circular outlines characterize a number of craters, particularly the largest ones; and features resembling slump blocks are found at the base of their inner wall slopes.
- 5) Some of the larger craters are girdled by rough terrain suggesting ejecta sheets of rubble.
- 6) Smaller crater clustering in random fashion was noted.

- 7) One or two broad domes were observed in crater floors.
- 8) Albedo differences between crater floors and surrounding terrain were observed, but without consistent pattern. Floors were either lighter or darker.

Chapman et al. (1969) Analysis. Two years after the final report of Leighton et al. (1967), Chapman et al. (1969) issued a more complete statistical analysis. The Chapman et al. conclusions are essentially similar, and will not be elaborated upon here. Their classification system consisted of four classes of crater degradation (Classes 1, 2, 3 and 4 represented fresh, less fresh, eroded, and 'ghosts' in essence, respectively), and a quality identification (Qualities A, B, and C denoted definite, probable, or uncertain crater, respectively). Some of the tabular results are shown in Table 4.

Mariner 6 and 7 Photography

The three Mariners have shown that cratered terrain is the most common type of terrain encountered on Mars. Cratered terrain seen in the Mariner 6 and 7 pictures were defined by Murray et al. (1971) as terrain in which craters are the dominant landforms recognizable at the available resolution (0.3 km at best).

The far-encounter (FE) views as well as the near-encounter (NE) views of the 1969 flybys have revealed that Mars, like the Moon, has an abundance of craters of all sizes, from the limit of resolution (0.3 km) up to several hundred kilometers across, and that there are roughly two distinct morphological types, which are described below, summarizing from Murray et al. (1971).

The first type, large flat-bottomed craters, ranges in diameter from about 15 km to several hundred km. They are highly modified from their presumed initial appearance as impact craters. Rims are missing or greatly subdued, central peaks rare and, if present, also quite levelled, rays are absent; the ejecta blankets or swarms of secondary craters commonly associated with large impact craters are degraded generally beyond recognition. Some, termed vestigial or 'ghost' craters, have only faintly visible wall relief. Thus,

Table 4. Crater percentages by class at several diameter intervals for Mars (Chapman et al., 1969).

Region	Class	Diameter Interval (km)					
		5-10	10-15	15-20	20-30	30-60	>60
Mars: pictures 4N7-14, Quality A and B	1	38	11	14	4	4	0
	2	58	26	24	9	8	14
	3	2	43	29	46	43	43
	4	2	20	33	41	54	43

one may distinguish two extreme states of preservation, or two subtypes of flat-bottomed craters (see, for example, 6N16 for comparison). Although various degrees of preservation can be seen within one crater population, no completely satisfying transition has yet emerged; perhaps this reflects complex episodic modification processes.

The second type, small bowl-shaped craters, is the majority of those with diameters below 10-15 km. Of fresh-looking appearance, they resemble the small lunar primary impact craters with their associated impact features, at least as far as the limit of resolution permits to see; for example, one cannot expect to see slump-blocks or secondary crater swarms. Apparently of remarkable uniformity, their morphology shows little degradation; hence, they must be the product of recent impacts.

In comparison with the lunar upland craters, the Martian flat-bottomed craters are less numerous and more highly degraded, and their intercrater areas are smoother. No large fresh-looking crater, such as Tycho, was seen; no rays and secondary crater swarms are present.

The local irregularities of the large old crater walls are usually preserved despite the smoothing of elevated rims and ejecta sheets. This indicates pronounced horizontal and regional redistribution of the material, rather than a local one from impact fragmentation and slumping as on the Moon.

Neither dark maria nor lava-flooded plains were detected, but this does not rule out their presence. Detection may be difficult if they have been thickly covered by dust.

Features other than craters are present in this terrain, such as sinuous channels and ridges, as well as some short linear subparallel markings. No sinuous "rilles," flow fronts, and partially flooded craters, which are so characteristic of lunar maria, are seen.

The small bowl-shaped craters seem to be morphologically similar to those of the Moon.

Correlations were sought by the CIT team (Murray et al., 1971), but no significant correlations were found between cratered terrain and latitude, or dark/bright areas, or topography. However, the analysis was only general.

Mariner 6 and 7 Crater Statistics and Analyses

Complete crater statistics covering the entire set of pictures returned by the two spacecraft in 1969 are not yet available. Only three studies of size-frequency distributions of craters can be presented here, with their tentative conclusions, and with no attempt to unify them.

Murray et al. (1971) Analysis. Murray et al. (1971) made a count over the Deucalionis Regio region (using frames 6N17-22). The plotted results were given as an average curve for the set of 6 frames (see Fig. 13) and as curves for the individual frames (see Fig. 14). The abundance or density plots

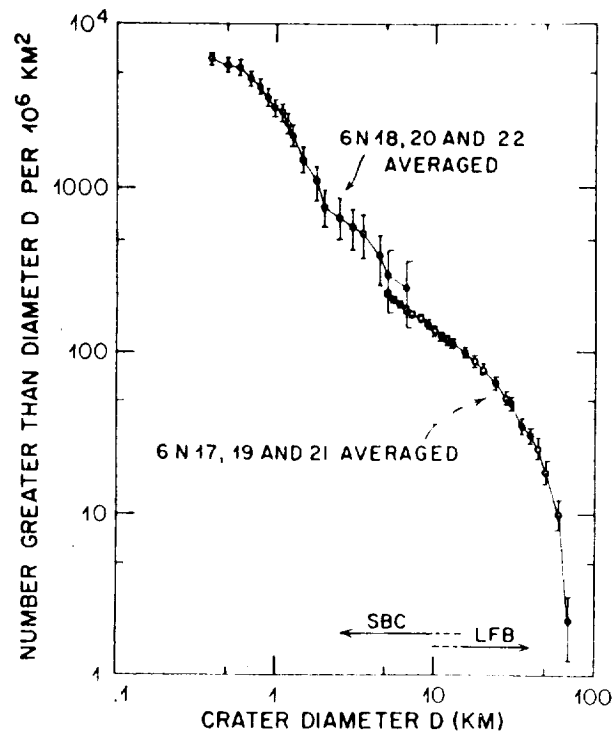


Fig. 13. Cumulative size-frequency distribution of craters in Deucalionis Regio (Murray et al., 1971).

are in the traditional "lunar" form; i. e., logarithmic plots in terms of cumulative numbers of craters larger than a certain diameter per unit area ($\text{km per } 10^6 \text{ km}^2$).

Examination of Fig. 14 disclosed that (1) there are no major areographic variations in the large (flat-bottom) craters density in Deucalionis Regio (data is from A-frames), and (2) there are apparently large areographic variations in the small bowl-shaped craters (data is from both A- and B-frames), but these are considered by the authors as not more than "possible minor" variations, because they feel that their counts are unrepresentative of the small crater population in the 5-15 km range, due to inadequate resolution of the A-frames and insufficient areal coverage of the B-frames.

Comparison with lunar crater curves was also made (see Fig. 15). The general conclusion was that the Martian craters have a similar overall distribution in form, except that (1) there is undersaturation for small and large Martian craters, and (2) the distribution for the small craters diverges significantly from that of the lunar uplands as size decreases, which again may be due to unrepresentative counts.

From the uniformity of appearance of small bowl-shaped craters, Murray et al. (1971) believe that the more recent crater modification history on Mars has probably been episodes of crater removal coupled with continuous rate of formation.

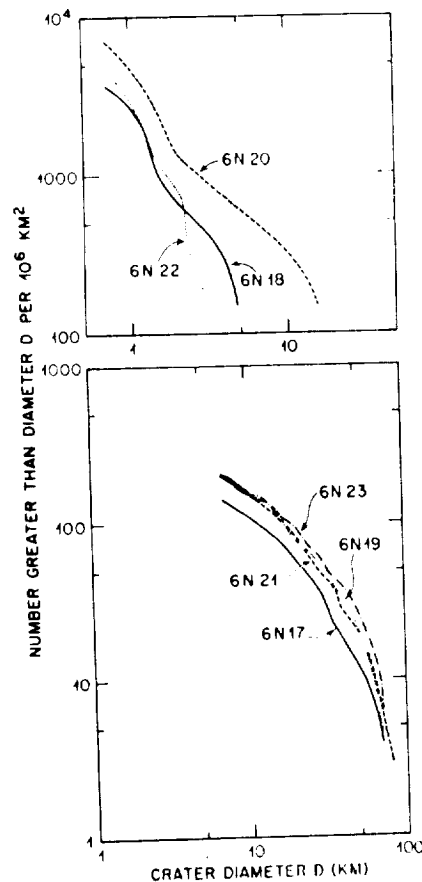


Fig. 14. Plots of crater abundances (similar to those in Fig. 13) for individual wide-angle (A) and narrow-angle (B) frames (Murray et al., 1971).

Woronow and King (1971) Analysis. Woronow and King (1971) made counts over the Meridiani Sinus and immediate surroundings in Deucalionis Regio, Thymiamata, and Edom.

Their analysis of size-frequency distributions of craters on both A-frames (6N11, 13, 19, and 7N25) and B-frames (6N10, 12, 18, 20, and 7N6, 22) obtained the following results:

- 1) The size-frequency curves for the four A-frames closely coincide (Fig. 16). Such a distribution may be representative in general of the Martian crater population observed on the large scale recorded by the A-cameras.
- 2) The curves for the B-frames do not cluster as well as A-frames and diverge most at diameters well above the B-frame resolution limit (Fig. 17). The observed discrepancies appear to be due to a combination of two reasons: (1) insufficient number of craters on any one image to provide a significant sample size capable of defining the populations, and (2) true differences in the populations of the smaller craters in the different image areas.

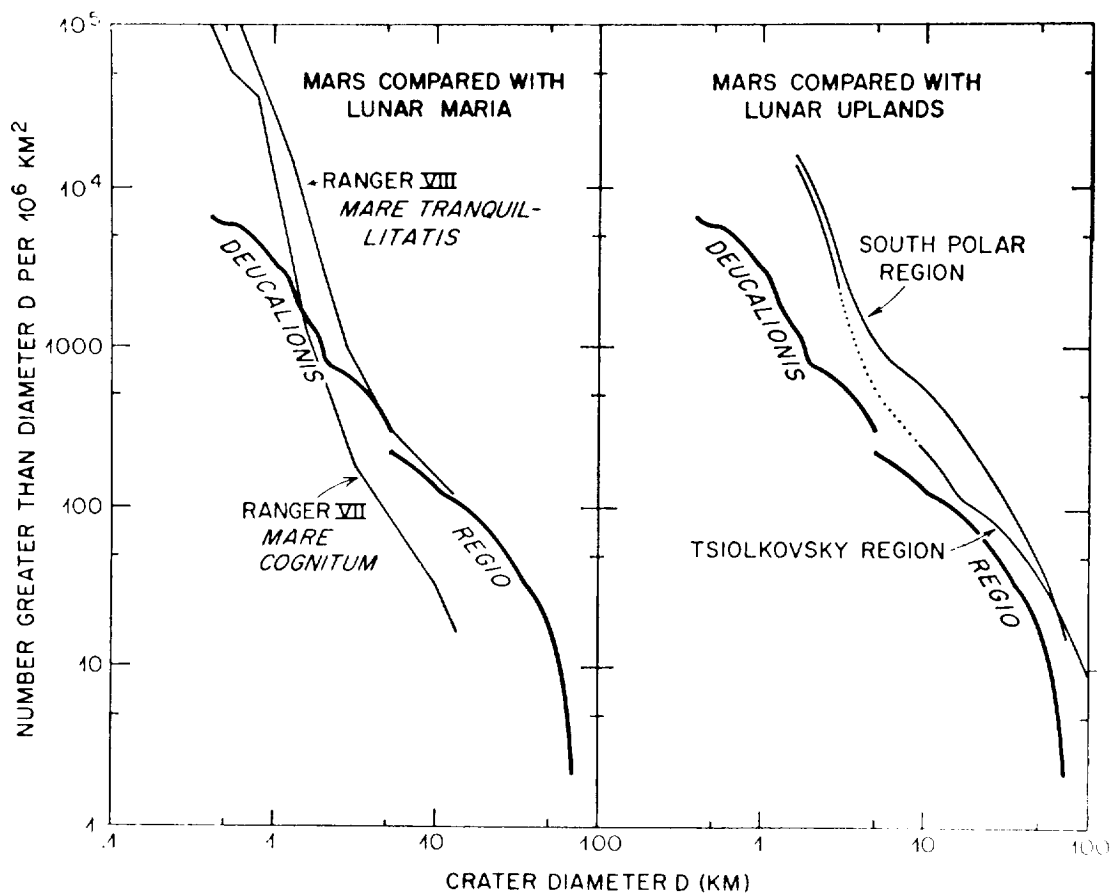


Fig. 15. The Deucalionis Regio crater abundances of Fig. 13 compared with those of the lunar maria (left) and the uplands (right) (Murray et al., 1971).

- 3) When the bright and dark area portions, which cover Meridiani Sinus and immediate surroundings in Deucalionis Regio, Thymiamata, and Edom (frames 6N11, 13, and 19), were plotted separately, a significant displacement of the two curves was found in the 20-50 km diameter range. The divergence is due to a greater percentage of large craters on the bright area terrain and a greater percentage of small craters (less than 15 km) on the dark area terrain.
- 4) A greater total crater density is apparent in the dark area.

The authors' interpretation of item 3) and 4) results is as follows:

A longer impact exposure age for the bright areas (to account for its greater density of larger craters).

A possible greater production of endogenetic craters in the dark areas (to account for its greater total crater density).

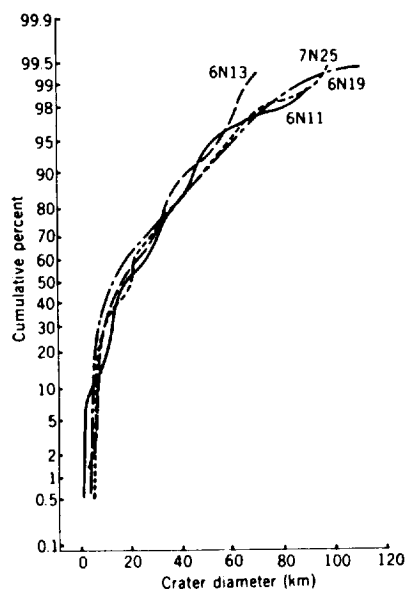


Fig. 16. Cumulative size-frequency probability distributions of craters found in wide-angle frames (Woronow and King, 1971 and 1972).

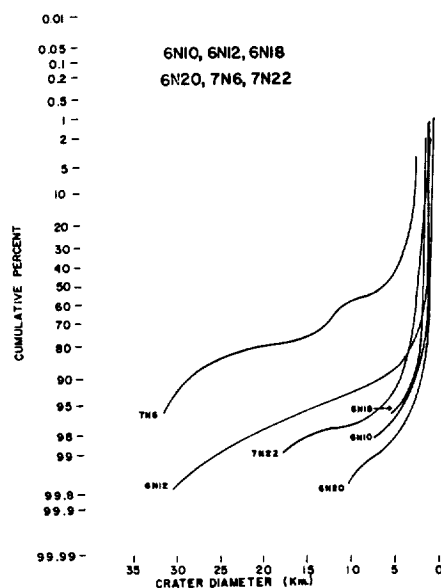


Fig. 17. Cumulative size-frequency probability distribution of craters found in six narrow-angle frames (Woronow and King, 1971).

NOTE: The "frequency distributions were plotted with probability ordinates, so that random samples from like populations or the same population would graph identically, provided that the sample size is sufficient" (Woronow and King, 1972). "This eliminates the necessity of normalizing the crater count to a unit area" (Woronow and King, 1971).

More rapid erosion and filling of craters--particularly the small sizes--in the bright areas (to account for the greater percentage of smaller craters and greater total crater density in the dark areas).

McGill and Wise (1971) Analysis. McGill and Wise (1971) obtained more extensive statistics aimed toward a study of the regional variations in average density of craters of various sizes and their degree of topographic degradation, for an area about 4.6 million km² lying within the four regions Meridiani Sinus, Margaritifer Sinus, Deucalionis Regio, and Hellespontus-Noachis. They used frames 6N10, 12, 13, 16, 17, 18, 19, 20, 21, 22, and 7N24, 25, 26. Each crater was classified according to its size and a "degradation number," which is the sum of score values from 1 (fresh) to 4 (highly degraded) assigned to their rim, their inner wall, and their floor, as systematized in Table 5. Thus the degradation number or class may range from 3 (sharpest craters) to 12 (barely visible 'ghosts'). The Mariner imagery resolution permitted classification by this degradation number of craters in only two size ranges: "small craters" (diameters 1-8 km) on B-frames and "large craters" (diameters greater than 16 km) on A-frames.

Results:

1) Density of Craters

The size frequency distribution plots (Fig. 18) resemble those of other authors, but they reveal that significant regional differences exist only for small craters (1-8 km). The fall-off toward the limit of resolution is greatest for Hellespontus-Noachis, then Meridiani Sinus, and least for Deucalionis Regio. Since this order is the same as that of their average degradation numbers, (see 2) Degree of Degradation), it suggests that the fall-off is due to the fact that difficulty in recognizing small craters increases with degree of degradation.

2) Degree of Degradation of Craters

The comparison of average degradation numbers for small and large craters in each of the four regions (see Fig. 19) shows that there are significant regional differences only for the small crater category. Thus, Deucalionis Regio appears to have fresher small craters on the average than has Meridiani Sinus.

Furthermore, the plots (not shown here) of degradation number versus crater density, for the various sizes, indicate that disparity in degradation exists only in the small crater sizes, becoming increasingly apparent as size decreases, and that marked distinctions exist between the regions. Thus, Deucalionis Regio has a great abundance of fresh 1-2 km craters, while Margaritifer Sinus has many moderately degraded small craters.

Table 5. Classification of Martian craters by degradation number (McGill and Wise, 1971).

Total degradation number for a crater is the sum of values for rim, inner wall, and floor.

Point Value	Rim	Inner Wall	Floor
1	Sharp, strong relief	High and steep	Cup-shaped (small craters) or with well-defined central peak (large craters)
2	Moderately strong relief	Moderately strong relief	Part of floor, flat and featureless
3	Barely visible	Barely visible	Mostly flat and featureless
4	Completely absent	Completely absent	Entirely flat and featureless

The contrasts in degradation-density curves of the small (1-8 km) craters in between the four regions are summarized in Fig. 20. Of the three possible interpretations given by McGill and Wise, their favored was a uniform degradation of small craters formed locally in episodes (or bursts). All four curves show an increase in crater density toward the degraded end of the plot, where, they suggest, a steady-state distribution is reached (assuming that the degradation number is some function of age). In Fig. 21, they illustrate the hypothetical chronological sequence of degradation-density curves for small craters.

For the large craters, McGill and Wise find a wide range of degradation numbers, but with the density progressively increasing with degradation. This argues against a twofold division into "degraded" craters predating and "not degraded" craters post-dating some global catastrophic event. They caution that this may not apply to "the very largest and oldest craters, which are inadequately sampled at present and may represent a distinctly different, primordial catastrophic period." They find the apparent absence of fresh, large craters (Copernicus-type) "expectable if their predicted rate of formation is very small compared to the rate at which topographic details are modified by Martian surface processes" and that the expected abundance of such craters estimated by Murray et al. (1971) was "based on an extrapolation of the apparently anomalous high density of small fresh craters in Deucalionis Regio."

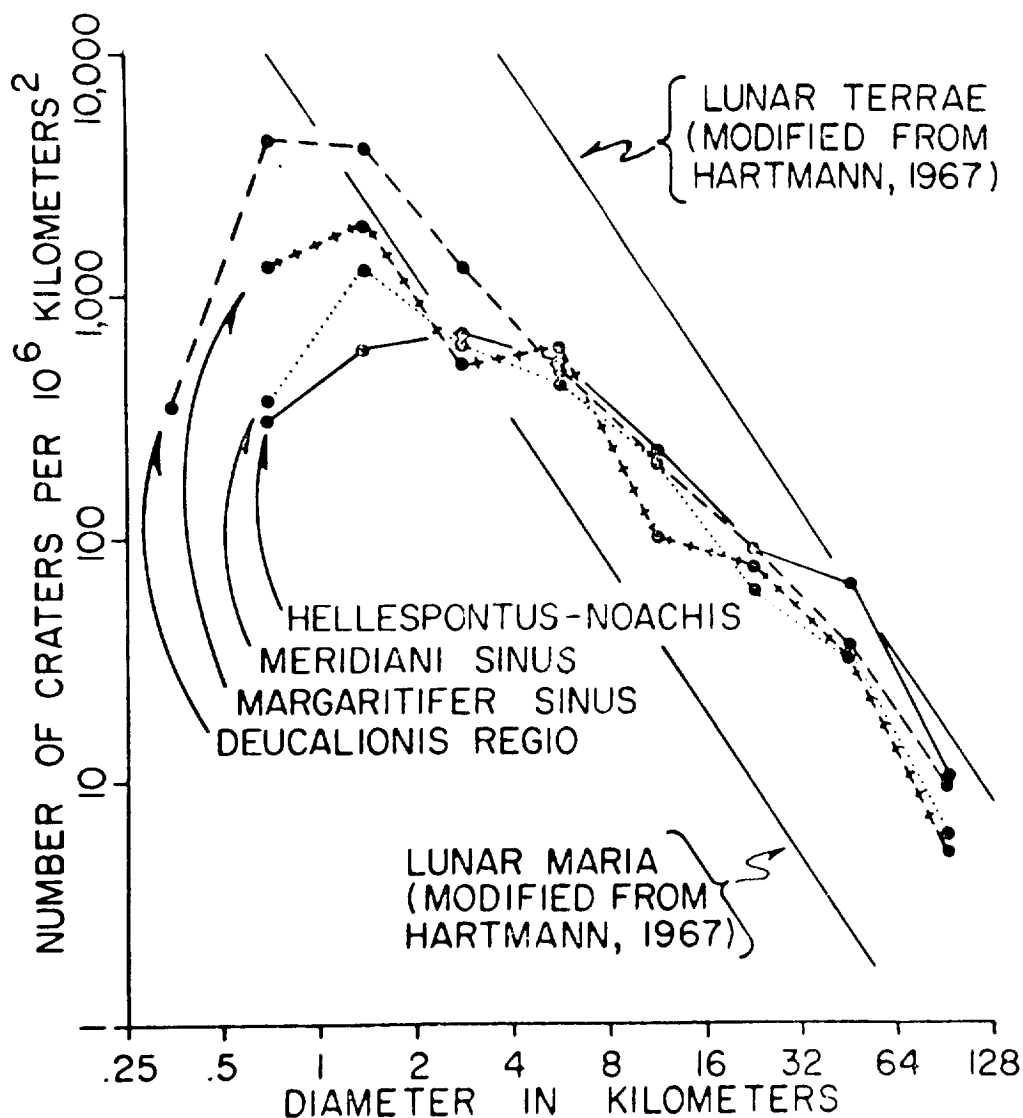


Fig. 18. Size-frequency distribution of Martian craters in four regions (McGill and Wise, 1971).

The almost continuous sequence of degradation found by McGill and Wise for small Martian craters was not accepted by some geologists (for example, Murray, Soderbloom) on the grounds that small degraded craters are too difficult to see and to classify reliably, especially when seen at large slanting ranges at the resolution of the B-frames of Mariners 6 and 7. Also, the subjectivity of the new classification scheme yielding a degradation number for each crater has been looked upon suspiciously. Nevertheless, the authors claim that useful, "reasonably reliable data" has been obtained by their scheme.

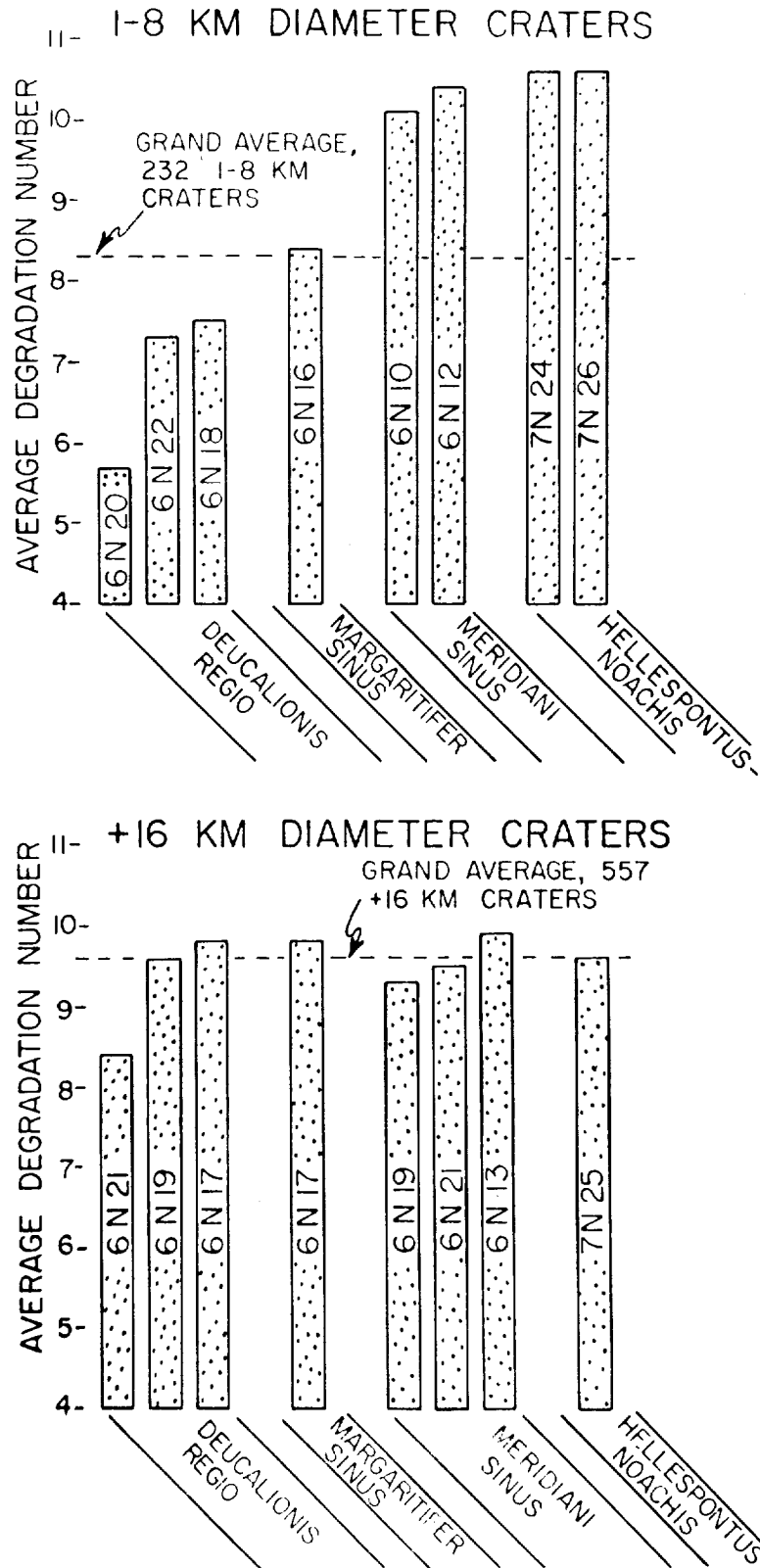


Fig. 19. Average degradation numbers for small craters (above) and large craters (below) in four Martian regions (McGill and Wise, 1971).

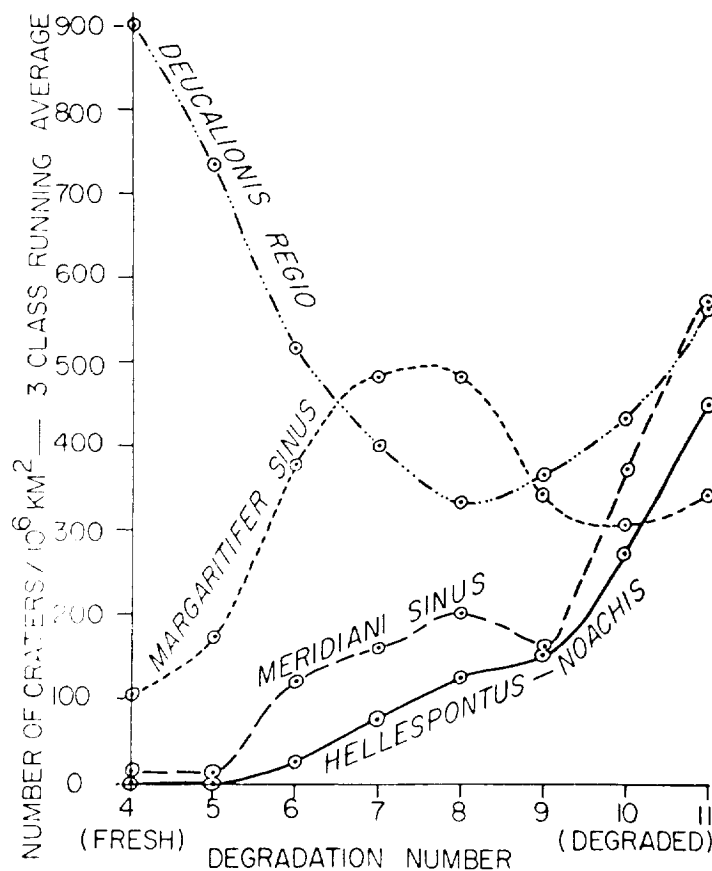
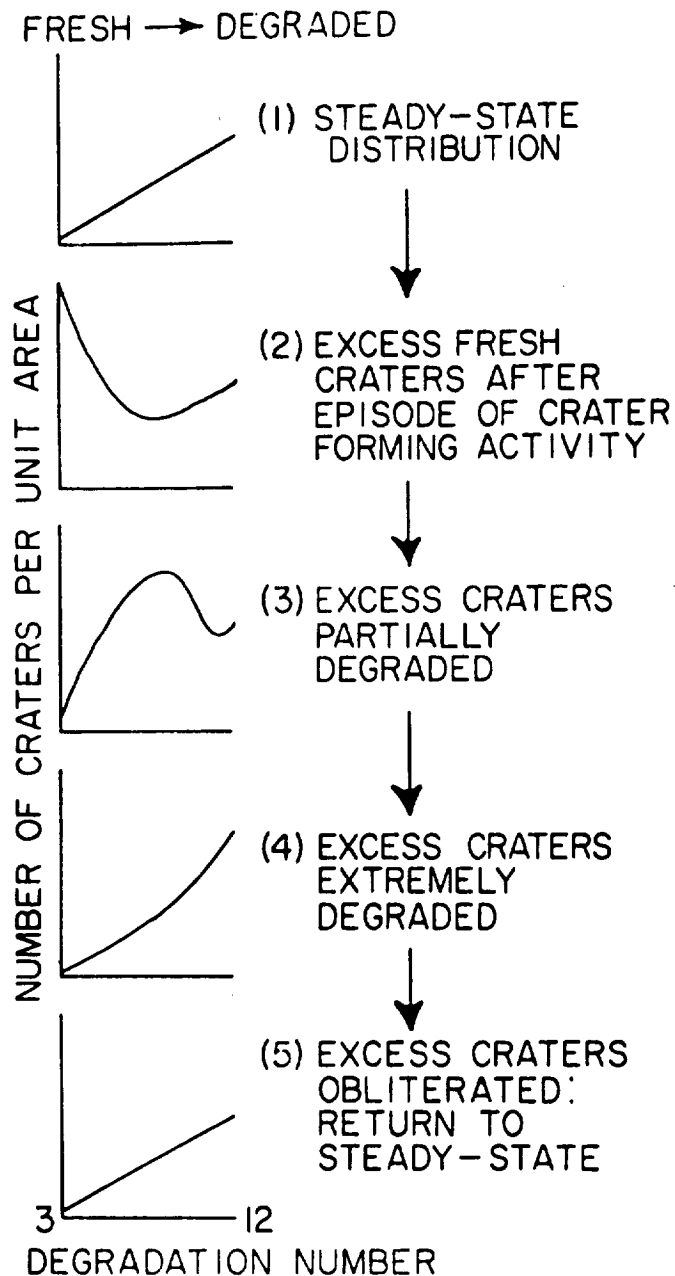


Fig. 20. Summary plots contrasting distribution of small (1-8 km diameter) craters among degradation classes in four Martian regions (McGill and Wise, 1971).

Crater Modification Processes

From analysis of the Mariner 4, 6, and 7 pictures, only a few crater modification processes are thought to be operative under the present conditions existing on Mars, which lacks substantial amounts of water. There are three important exogene processes to consider, as follows:

- 1) Meteoroidal impact fragmentation and obliteration must be similar to that on the Moon, except for the slight retarding effect of the thin Martian atmosphere. Dycus (1969), however, calculated that the 5-mb atmosphere has no appreciable effect upon the impact velocity of objects creating craters larger than about 10 meters. Direct-hit impacts can partially or completely obliterate the existing craters, depending upon the size, velocity and course of the impacting body. Significant erosion or damage by a nearby impact still can occur, either through the filling in of the existing crater by ejection of debris or indirectly by mass wasting (downslope mass movement) through the propagating shock wave along the surface.



Stages (1) through (5) represent a chronological sequence with unknown time scale.

Fig. 21. Model explaining differences in degradation - density curves for small craters from four Martian regions (McGill and Wise, 1971).

One certain result is that much impact rubble is produced, and the Mars surface, with its many craters, must be thickly mantled by such debris. Chapman et al. (1969) attempted quantitative treatment of the impact erosion process, sometimes called pelting, and found that it seems to account for much of the damage sustained by the Martian craters.

- 2) Aeolian erosion and deposition can be very effective on a dusty/sandy surface, such as that of Mars, provided the winds are sufficiently strong and frequent. The aeolian mechanism is through transport of dust or sand-sized particles, either by suspension, saltation, or traction, depending upon the strength of the wind. It appears from the studies of Gierasch and Sagan (1971) that local topographic (or slope) winds, induced thermally by sharp relief on Mars, can alone reach considerable velocities of the order of 50 msec^{-1} (180 kmhr^{-1}) and even greater (100 msec^{-1}) above the surface boundary layer; and, if superimposed on the global seasonal thermal wind (which itself can reach 50 msec^{-1} , according to the Leovy and Mintz 1969 calculations), such winds appear to be an adequate driving force, since it was estimated that wind velocities about 80 msec^{-1} were required to raise particles 400μ in diameter in low areas under a surface pressure of $p_0 = 10 \text{ mb}$ (Sagan and Pollack, 1967, 1969). This recent optimistic view has stemmed from the new knowledge that Martian topography is highly variable. Similar calculations were performed by Arvidson (1972) for surface pressures of 6 to 7.6 mb, and the results are given here: see Fig. 22 for the threshold drag velocities and Fig. 23 for the corresponding lowest threshold wind velocities (at 1 m.). Settling velocities for spherical particles have also been estimated by Arvidson (1972), see Fig. 24.

Another line of studies undertaken by Ryan (1969) and centered on explaining the yellow clouds on Mars as resulting from a dust-devil generation mechanism concludes that the high threshold velocities required for the suspension of dust under surface pressures $p_0 = 5$ to 10 mb are likely to be attained in the larger of these vortices.

Crater obliteration on Mars by aeolian dust deposition (especially of small craters) has recently been discussed by Hartmann (1971b).

- 3) Mass-wasting, namely the downslope movement of loosened material (rock, debris, soil) under the influence of gravity is another crater modifying or levelling process which must be operative on Mars. Shearing stresses due to gravity exist in every slope, constantly causing a very slow, continuous downslope movement known as 'creep'. When the shearing force reaches the failure point, a sudden rapid collapse of mass called 'landslide' can occur. Mass-wasting is promoted by thermal expansions and contractions, freeze and thaw, seismic events, vibrations from meteoroidal impacts, loading at top of slope (by aeolian deposition, for example), also weathering (decreasing the strength of the material).

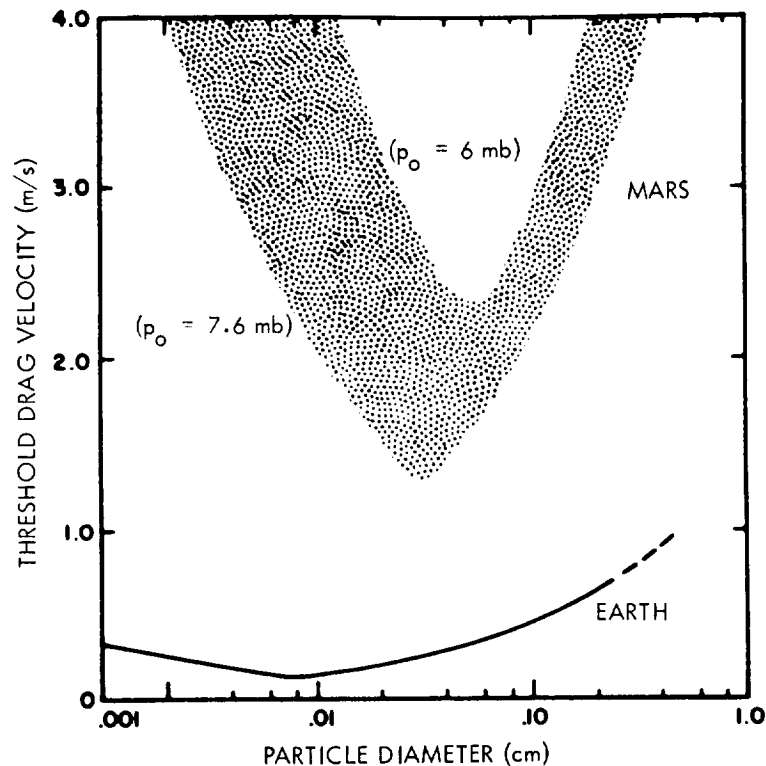


Fig. 22. Threshold drag velocities plotted over a range of particle sizes for Mars and Earth. Earth curve after Bagnold (1941). Particle density for Martian curves = 3.0 gm cm^{-3} (Arvidson, 1972).

Thermal creep was advanced by Sharp (1968) as probably quite effective in modifying Martian craters, because of the large diurnal fluctuations of temperature. It is difficult yet, however, to assess its importance on Mars, since the effectiveness of this process depends on many parameters (slope angles, structure of the rubble layers, coefficients of friction, etc.) in addition to temperature fluctuations.

Processes such as thermal fracturing are considered ineffective on the Moon by Ryan (1962) while freeze and thaw proposed by Wade and DeWys (1968) requires a substantial permafrost layer, thus being still speculative for Mars.

Other possible crater-modifying processes, not evident in the cratered terrain photographed by Mariner 6 and 7, would include endogene processes: volcanism under various forms (lava flows and flooding of crater floors, ash deposits, etc.) and tectonism (crustal readjustment through faulting), orogeny (mountain building), and geothermal activity. Thus for example, Pike (1971) drawing from certain similarities between lunar and Martian craters above 10-20 km indicated the probable importance of: (1) slow or gradual tectonic adjustment, and (2) localized magmatism in large Martian craters. Green (1971) claims evidence of volcanism in some large craters observed by Mariner 4.

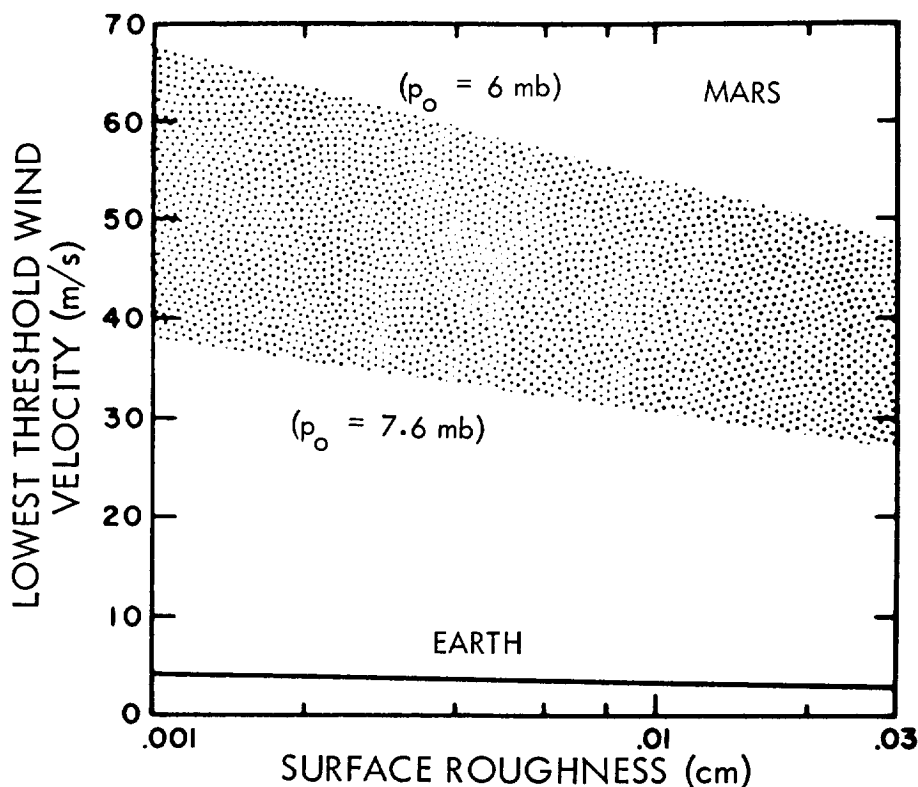


Fig. 23. Lowest threshold wind velocities for Mars and Earth (1 meter above surface). Maximum surface roughness for terrestrial deserts = 0.03 cm (Ryan, 1964). Lower bound was set arbitrarily (Arvidson, 1972).

Age of the Large Craters

The large and well-eroded, flat-bottomed craters, visible in pictures obtained by all three Mariners, are undoubtedly very ancient structures, apparently several aeons old. They may be "primeval" craters dating from the end of the planet's major accretional phase, or they can be "later" craters. Differences of opinion concerning these craters existed between the experts in 1965. After Leighton et al. (1965) announced that the craters must be 2-5 billion years old, a series of criticisms appeared (Anders, 1965; Baldwin, 1965; Witting et al., 1965) with much lower estimates, around 1 billion years old. Subsequently, Öpik (1965), Hartmann (1966), Binder (1969), and Chapman et al. (1969) estimated that the craters must be at least 4 billion years old, and this estimate became generally accepted. After the Mariner 6 and 7 flybys, Murray et al. (1971) declared that these ancient structures must be the survivors of the accretional phase some 4.5 billion years ago, while Hartmann (1971a) finds as a result of his analysis, that they cannot go that far back and apparently are slightly later craters surviving from an early intense erosional phase on Mars. Three lines of evidence are given by Hartmann: (1) under-saturation compared to lunar upland craters, (2) possible preservation of the

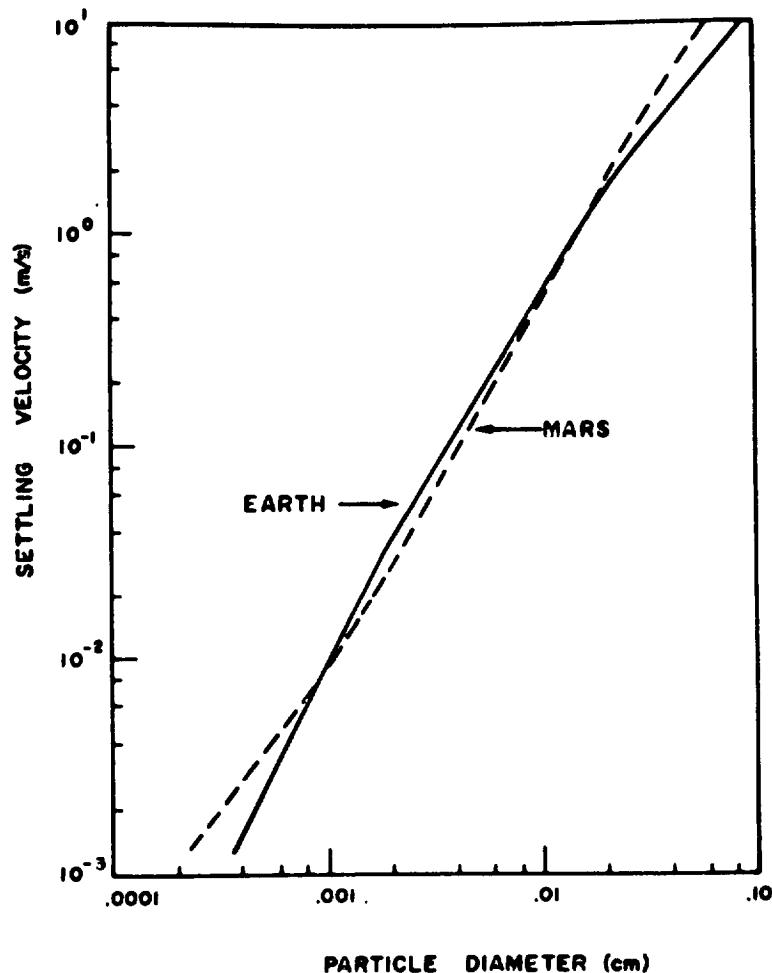


Fig. 24. Settling velocities over a range of particle sizes for Mars and Earth. Earth curve after Ryan (1964). Martian curve is an average of the curves for surface pressures $p_0 = 6$ and 7.6 mb. (Arvidson, 1972).

fossil asteroid mass distribution, and (3) extrapolation backward a few aeons of the asteroidal impact rate can account for most of the craters. He hypothesizes that a severe erosional phase wiped out all the original accretional craters, and that those we currently observe are the product of a lesser, but still intense, bombardment period which extended for some 10^8 years after accretion. One very pertinent observation is that the intercrater areas are quite smooth, reflecting the mentioned undersaturation of craters. An early short-lived, dense atmosphere on Mars has been proposed by several authors: on lithological grounds by Binder and Cruikshank (1966), and on geochemical grounds by Fanale (1971).

Chaotic Terrain

The Mariner 6 TV photography revealed a rough, uncratered type of terrain which Sharp et al. (1971a) described as "chaotic" because of its appearance as an irregular jumble of topographic forms. "Chaotic terrain consists of a rough, irregular complex of short ridges, knobs, and irregularly shaped troughs and depressions" at the kilometer scale (Sharp et al., 1971a). It is best seen in the high-resolution (B) frames 6N6, 8, and 14. In frame 6N6, a northeasterly grain is noticeable. Chaotic terrain essentially lacks recognizable craters; only three small, faint, marginal ones were "tentatively identified." It is difficult to recognize small craters (<5 km) amidst the jumble of features. The contact line between chaotic and cratered terrain is irregular and not always well defined. The transition from cratered to chaotic terrain often is sharp and marked by abrupt structural patterns: apparently arcuate scarps, blocks and ridges with intervening depressions on the chaotic side, and apparently huge cracks on the cratered side of the contact line (see 6N8 and 14), which suggests a definitely lower elevation of chaotic terrain. Confirmation of this lower elevation was in fact given by the Lincoln Laboratory (1970) radar results, as well as by the Mariner IRS CO₂-pressure results (Herr et al., 1970) over these equatorial areas.

The albedo of chaotic terrain often contrasts with adjoining cratered terrain; usually, but not necessarily, it appears brighter.

Distribution

Subsequent to the discovery of some 12,500 km² of characteristic chaotic terrain in the B-frames previously mentioned, a much greater area--about 1.5 million km²--of possible chaotic terrain was delineated in A-frames 6N5, 7, and 9, as illustrated in Fig. 25. This interpretive map was constructed by extending the chaotic-cratered contact line, traced from the B-frames onto the A-frames, "on the basis of structural patterns, crater distribution, brightness contrast, and characteristic regional trends" (Sharp et al., 1971a). The distribution of postulated chaotic terrain appears highly irregular, like lace-work, with odd-shaped, sometimes disconnected, patches. Areographically, this distribution is within equatorial latitudes 15°N to 15°S and is centered in Pyrrhae Regio (a mixed dark and bright area), with extensions into the dark areas Aurorae Sinus and Margaritifer Sinus, as well as into bright area Chryse. It is quite possible, however, that chaotic terrain is present elsewhere on the Martian surface in areas not photographed by the Mariners. In fact, the Mariner 4 frame 4N2 shows "irregular streaky patterns," hinting at possible chaotic terrain near 25°N, in Amazonis, northeast of Trivium Charontis.

Relative Age

The distinctively fresh and sharp topographic features of the chaotic terrain, especially at its contact with adjoining cratered terrain, the lack of craters, and the low elevation, all suggest that it "formed at the expense of cratered terrain" (Sharp et al., 1971a) and is relatively young. At least, it is younger than the large (>15 km) flat-bottomed craters, since these are definitely erased. It is not clear whether the chaotic terrain is as young as the small bowl-shaped craters seen on adjacent cratered terrain.

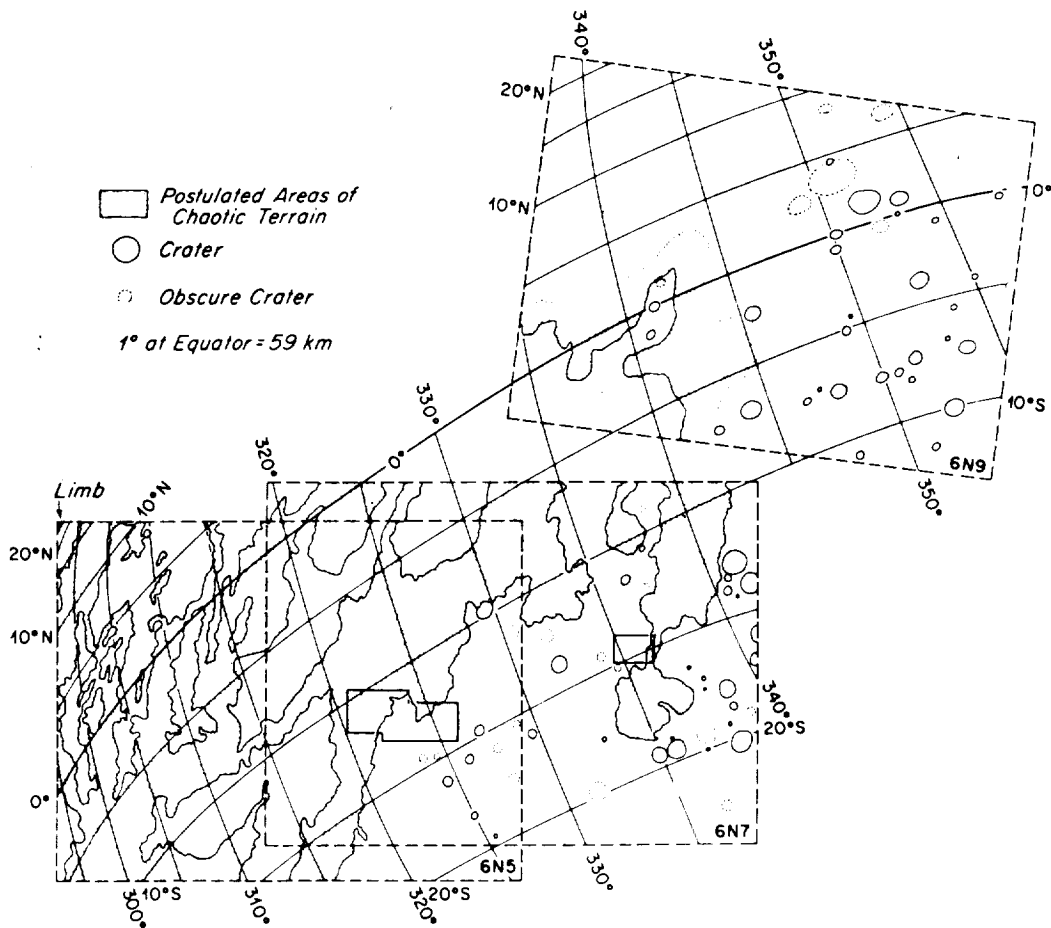


Fig. 25. Interpretive map of chaotic-terrain distribution constructed from Mariner 1969 photos (Sharp et al., 1971a).

Origin and Possible Processes

The following speculations on the mode of formation of chaotic terrain have been made by Sharp et al. (1971a). If chaotic terrain is younger than cratered terrain, then it must be the result of either some recent events or some continuous processes erasing most craters. No analogs can be found on either the Moon or the Earth. The irregular, hummocky terrain seen on the Moon in the Montes Apennines, Mare Vaporum, and Cassini quadrangles are ejecta sheets formed by asteroidal impact and/or volcanic explosions, and not depressed areas. On Earth, large-scale collapse usually results from volcanism, but the calderas and volcano-tectonic formations developed do not have the geometric form or distribution pattern found in Martian chaotic terrain. The unusual features of the latter are similar to those found in terrestrial collapse, slumps, and slide areas; however, their scale is much larger. It is difficult to explain such large-scale mass movements on Mars in a relatively stable, recent period. It would be necessary to have enough large impacts and fair regional slopes of the bedrock to permit movement of loose impact rubble induced from vibrations of these large impacts. This is

unlikely. Other possible explanations, such as collapse from decay of segregated bodies of ice (developed earlier in Mars' history), or even aeolian deflation, are also difficult to support. Processes of internal origin, such as volcanism accompanied by defluidization and/or tectonic deformation, might be closer to the correct explanation. This, however, would presume that these processes are an expression of a recently begun maturing stage in Mars' geothermal evolution (Sharp et al., 1971a). Recent models of the Mars interior (Anderson, 1972) do favor a melted core and partial differentiation (see Section 2, Interior).

Featureless Terrain

Another type of uncratered terrain, called "featureless," was discovered in the Mariner 7 TV photographs 7N27-30 over the southern bright area Hellas. Featureless terrain was defined by the CIT geologists (Sharp et al., 1971a) as terrain which appears to lack any kind of recognizable topographic features at the available 1/2-km resolution and over sizable expanses.* It has, therefore, the appearance of smoothness in the pictures mentioned, but with improved resolution this may not be the case. The irregular, diffuse variations in shading seen may be due to gentle surface undulation under a low Sun or albedo differences of the ground. The possibility of ground clouds or haze obscuring the surface was considered but was discarded after careful scrutiny of both FE and NE sets of pictures.

So far, featureless terrain has been found only in Hellas. The A-frames covered about 65% (1.6 million km²) of Hellas, and revealed only a mesa-like knob some 300 km east from its Hellespontus border (Thorman and Goles, 1971), three small flat-floored craters near this border (Sharp et al., 1971a), see 7N27, and possibly two ghost craters toward the center (see improved versions of 7N29). Only two B-frames, confirming the lack of features (7N28 and 30), were taken over Hellas, but it was inferred that probably most of Hellas is featureless.

The change in morphology from featureless Hellas to heavily cratered Hellespontus proceeds rapidly through a transition zone some 150-350 km wide. This zone displays, in addition to the flat-bottomed type crater found in Hellespontus, a "series of discontinuous overlapping scarps and narrow ridges, individually 20-90 km long" and facing Hellas (Sharp et al., 1971a). There appears to be no small bowl-shaped craters. This zone is darker than Hellespontus proper and forms a sharp albedo contrast with bright Hellas. The contact line with Hellas is quite irregular and poorly defined topographically, except near 45°S (latitude of center of Hellas), where "there is an abrupt change from cratered to featureless...marked by an irregular east-facing escarpment" (Thorman and Goles, 1971). The abundance of large and small flat-bottomed craters in the transition zone appears similar to that of Hellespontus. The statement by Sharp et al. (1971a) that "nowhere do the scarps or ridges crosscut flat-bottomed craters; rather, the craters appear to interrupt or deform the ridges" was contradicted by a number of example cases pointed out by Thorman and Goles (1971). (See their diagram, Fig. 26,

*An area at least 10,000 km², to avoid confusion with the smooth intercrater areas lying usually within cratered terrain.

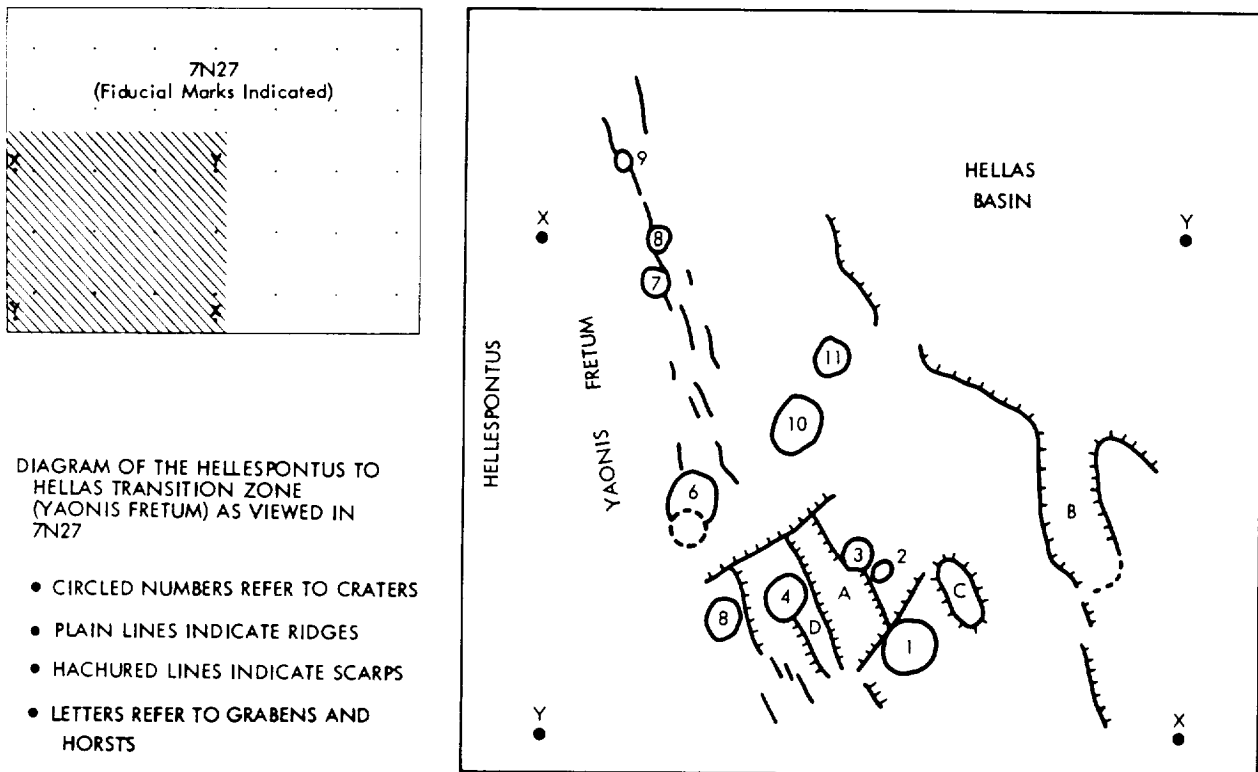


Fig. 26. Diagram of the Hellespontus to Hellas transition zone (Yaonis Fretum) as viewed in 7N27 (Thorman and Goles, 1971).

of an enlargement of the zone viewed in 7N27.) In fact, these authors find evidence of more cases against than for Sharp's statement. They also found that not all scarps face Hellas: they indicate on the same diagram, the presence of at least two "grabens" (indicated as A and B), one of which forms an embayment of Hellas into the transition zone. The same authors also report the presence of two north-trending "horsts" (indicated C and D) in the transition zone.

The morphology of the transition zone, with its ridges parallel to scarps facing Hellas, and the appearance of the contact line, reminiscent of creep, suggest a general slope downward toward Hellas. This confirms other data from Mariner 7 (see Topography subsection) indicating that Hellas is a large depression some 2 km below the mean Martian level and some 5 km below Hellespontus which is a high region. The circularity of Hellas certainly is suggestive of a basin.

Origin and Age of the Hellas Basin

Hellas, considered as a large circular depression, appears to be extremely old, dating perhaps as far back as the planet's accretionary phase. Three possible modes of origin were considered by Sharp et al. (1971a): impact,

volcanic explosion, and subsidence. A combination of early accretionary impact and later isostatic subsidence "over a dense mass within the crust or near crustal interior (O'Leary et al., 1969)" to quote Sharp, seems more promising. Sharp et al. and Thorman and Goles are in agreement on this view.

The scarps and ridges of the transition zone appear to be related to, and may provide some clues concerning the formation of Hellas. For the time being, however, the question of their age relative to the craters of the zone is an unsettled matter: Sharp et al. (1971a) consider the scarps and ridges to be older than the old flat craters, arguing that they are distorted by them, while Thorman and Goles (1971) feel they are generally younger. In the latter case, the scarps and ridges would be accounted for by the late subsidence of Hellas, rather than by the early impact itself, as suggested by Sharp et al.

Origin and Age of the Featureless Floor of Hellas

The featureless floor of Hellas is thought to be the product of either a recent continuing surface process "capable of obliterating craters as rapidly as they are formed" (Sharp et al., 1971a) or a recent episodic event that swept the surface clean. Continuing surface processes include aeolian burial (by transport and deposition of dust), *unusually active creep, and basal surges associated with impacts (a less likely mechanism). Episodic events include volcanic extrusions (ash or tuff), fluidization of the rubble layer by volcanic gases, activation of creep and/or other mechanisms by geothermal warming, decay of frozen ground, and atmospheric cometary explosion. See Sharp et al., 1971a. Objections may be found for each of the processes listed, so that the origin of the featureless terrain remains cloaked in mystery.

3.5.4 SOUTH POLAR CAP

The Mariner 1969 photography provided the first close look at a Martian polar cap: the fully developed, cloud-free, early springtime South Polar Cap. The many FE pictures by both spacecraft, taken a half-million kilometers away, first revealed that the very irregular edge was due in part to the presence of many large craters, some exceeding 100 km in diameter. In addition, the cap's interior displayed an irregular mottling with features up to 300 km, which presumably represent real differences in the reflectivity of its surface. It was also noted that the fuzziness and limb darkening toward the morning terminator (on the west) may be due to a special photometric function of its surface (Leovy et al., 1971). Figure 27 shows the successive hour-interval views taken of the Polar Cap by Mariner 6. Marginal irregularities can easily be followed through their rotation with the planet.

Ten Mariner 7 NE frames, 7N10-20, taken at slant ranges of 5000-6000 km and oblique angles of 40°-48° from vertical, revealed in spectacular detail the structure of the frost cover from its edge, near 60°S, to the South Pole proper. It became clear that a rather well-cratered surface underlies the white, gleaming frost almost everywhere except near the South Pole, at least in the sector photographed (from 270° to 60°W). The frost cover

*An attractive process, in view of the denser air layer over Hellas.

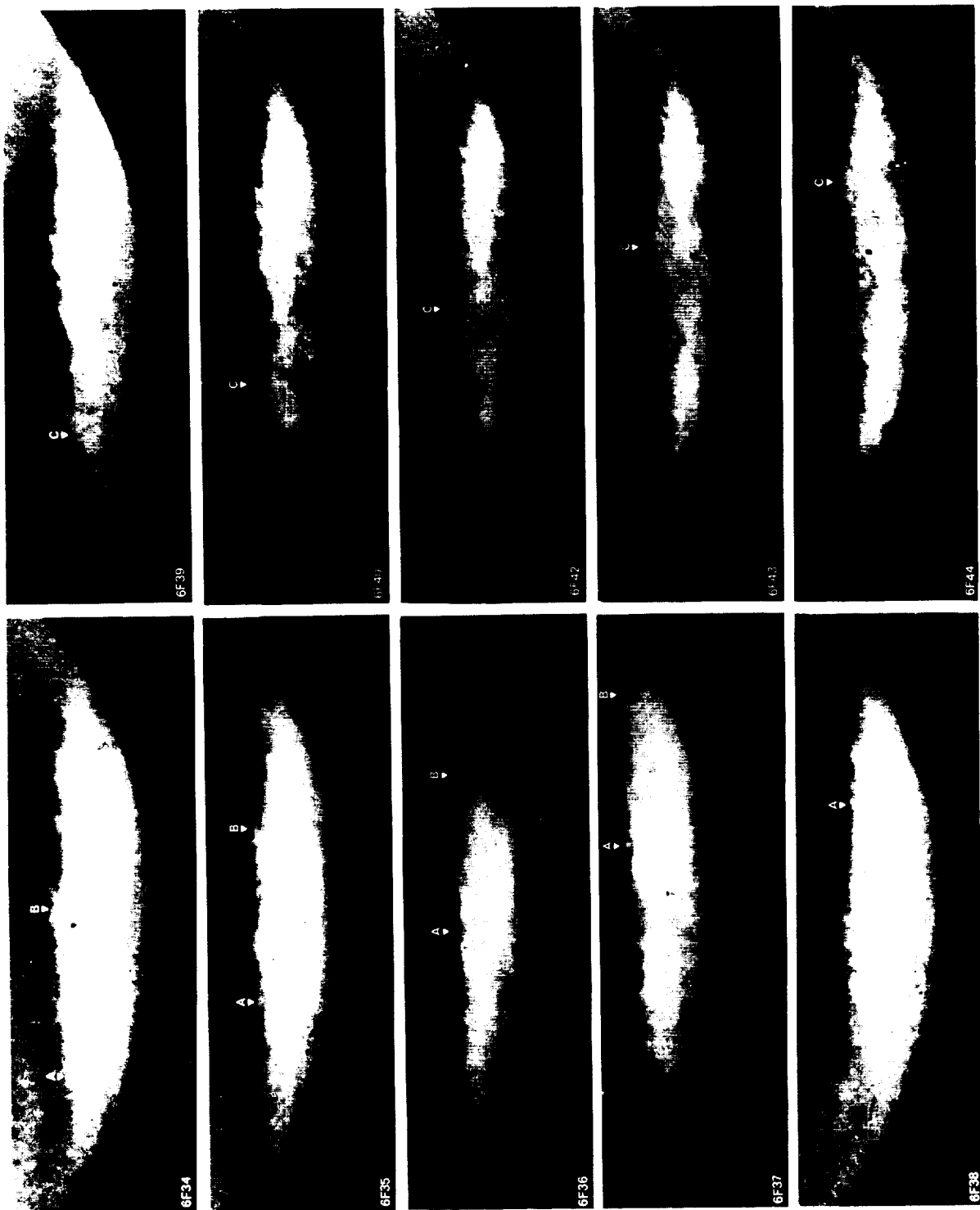


Fig. 27. Mariner 6 far-encounter views of South Polar Cap, enlarged to a common scale.
(Sharp et al. 1971 b)

appeared substantially thicker, although more variable, than previously thought. Also noted were a number of strange-looking "snowforms" or features which presently defy explanation.

Mariner 7 Photography and Observations

Morphology

In studying the pictures of the South Polar Cap, the analyzing team of CIT geologists (Sharp et al., 1971b) has distinguished the following three concentric zones: (1) the edge or margin, a narrow area subdivided into three subzones; extra, outer, and inner marginal subzones, (2) the interior, and (3) the central region.

Summarizing the findings of the CIT team, these zones are reviewed below.

1) Edge or Marginal Zone

- a) The extra-marginal subzone (7N11, 13) is the bare ground area (not frost-covered) just outside the frost patches of the cap at the time of photography, but still within the polar region limits or area annually covered by the extended polar cap. Here craters appear to be similar to and as abundant as those in other heavily cratered Martian terrain, and apparently are unmodified by the cap's annual waxing and waning. There is a lack of craters in the western third of 7N11, possibly due to cloud obscuration.
- b) The outer-marginal subzone (7N11-13, 15) is the immediate, sparsely frost-covered edge of the cap itself, or in the words of Sharp et al. (1971b), the zone "characterized by preservation of disconnected frost patches." This is to be viewed in the true-intensity mosaic (without AGC). The Max-D mosaic (with AGC) shows an unfortunate black band artifact here which is not to be interpreted as the classical dark polar collar seen from Earth. (When the AGC effect is removed, there is no suggestion of it.) But this cannot be used to disprove the existence of the dark polar collar, as the time of photography was too early in the Martian spring for its appearance. In fact, the polar collar was first seen in late September 1969, according to Capen (1970).

In this zone, the crater floors are frost-covered either completely, appearing as solid white ellipses, or partially, appearing as irregular white patches. Some of the southward-facing inner walls, sheltered from the sun, display lingering frost, appearing as white crescents, concave south. This frost accentuates crater visibility and ground topography in general. Also noted (7N11, right center) are "some scattered, irregular, dense white patches" (Sharp et al., 1971b), which may be mistaken for clouds (Leovy et al., 1971) but are more likely frost accumulations due to topographic irregularities.

- c) The inner marginal subzone (7N11, 13, 15) is a more deeply and irregularly frost-covered zone of ragged appearance. The frost cover is "essentially continuous except for islands of frost-free, or nearly frost-free, ground" which register dark to black in the Max-D pictures (AGC effect). Many craters are expressed "as dark-line ellipses owing to obliquity of views or as solid dark crescents concave north," with some displaying a dark central dot, possibly a peak (Sharp et al., 1971b). The visibility of abundant craters again owes much to frost accentuation.

2) Polar Cap Interior

The interior (7N13-20) is the zone largest in area, and is shown as essentially continuous frost cover with an abundance of craters and various other topographic features, some of which were unexpected.

Most craters display bright rims and darker floors, although the floors probably are not frost-free, because they do not appear black like the bare ground at the cap margin. The surrounding (inter-crater) surfaces are intermediate in brightness. Outlines of many large craters appear much more irregular, even ragged, compared to unfrosted ones, probably because of irregular frost accumulations on their rims. A few medium-size craters display peripherally "a radial pattern of short ridges and furrows" (7N19, upper center). Some craters have central white dots suggestive of central peaks. Craters over 15 km appear to be flat-floored, and some of 30-50 km size have distinct rims. Many smaller craters are bowl-shaped, with rims. Abundance is comparable to other well-cratered Martian terrain.

Unusual noncrater features are seen: irregular depressions with angular outlines appearing often in frost-filled craters; they were named "etch-pits." They have lighter rims and darker floors like the craters. Associated with them may be found "etch-furrows," or elongations of similar character.

Also found are "a series of short, parallel linear features aligned in a WNW direction" and seemingly connecting tiny nodes: they were called "beaded lineations." Other lineations elsewhere have less regular alignments. The cap in fact appears to be "a grooved, fluted, and scoured surface" (Sharp et al., 1971b). Smaller subdued features of positive relief also are present.

Interesting larger, irregular features of positive relief were noticed in frame 7N19. These are: one crater about 15 km across, surrounded by features resembling (again quoting Sharp et al., 1971b) "a pile of volcanic flows extruded from a central vent," then "an area of irregular hummocky terrain looking much like a lunar ejecta sheet," and "a belt featuring a number of short irregular ridges" of northeasterly trend.

Finally, some large (20-120 km across) irregularly shaped white patches and bands of high luminance were seen (7N17, 19) which, if they are not clouds (Leovy et al., 1971), remain unexplained.

3) Central Polar Region

The central region (7N17, 19, 20) is the region seen near the South Pole and presumably encircling it without necessarily being centered on it. Actually, only a sector of 165 degrees longitude (between 235° and 40°W) was photographed. Its boundary, with cap interior, east of the prime meridian (0°W) is well-defined, between 80-75°S and displays an abrupt crater-scalloped arc somewhat like the edge of a lunar mare. The boundary west of 0° is not as well defined. Craters are rare and barely visible in this central region, with one notable exception: the forefoot of a large crater pair called the "giant's footprint" crossing the boundary (see 7N19, 20). The most unusual series of sinuous linear features, appearing to spread out like waves from the pole, probably best characterizes the central polar region. Called "quasi-linear markings" by Sharp et al., these enigmatic lineations are conspicuous between 230° and 40°W, with lengths up to 300 km and widths of 10 km (see Fig. 28). Their separation varies, and gnarls are present, as well as segmentation. Faint indications of them swinging around the pole were detected in highly processed pictures.

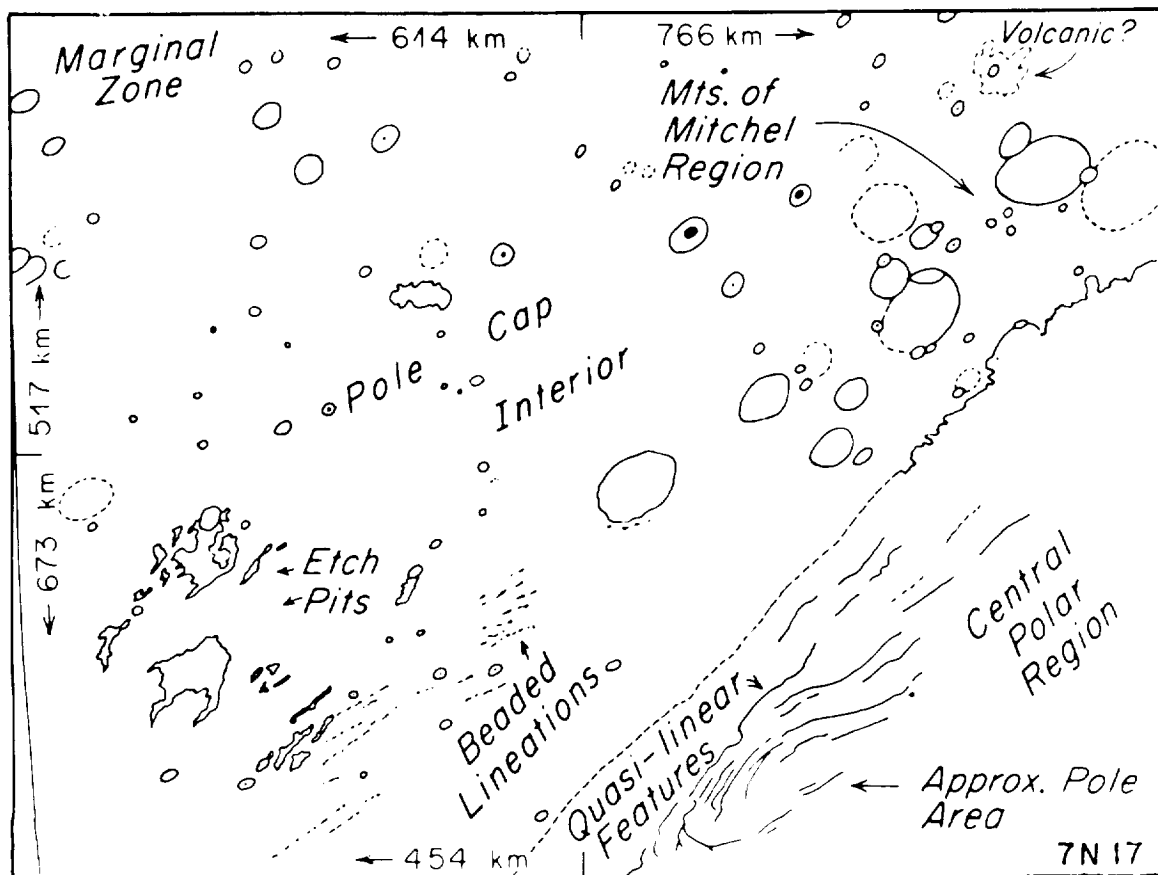


Fig. 28. Sketch of South Polar Cap: interior and central region, morphological features appearing in 7N17 (Sharp et al., 1971b).

Processes

Marginal Zone. Processes responsible for the lingering of frost in crater bottoms of the outer marginal zone are probably (1) protection from solar radiation and winds, (2) differential CO₂ vapor-pressure effect with altitude, rather than temperature, as discussed by Sagan and Pollack (1966). Similarly, in the inner marginal zone, the frost-free, or nearly frost-free, rims of craters and other high-standing features (central peaks, for example) are thus denuded for converse reasons.

Note: Gentle slopes (5° or less) for the individual topographic features of the marginal zone were inferred from frost wastage (denudation) observations, assuming only solar radiation (insolation) is responsible (see Sharp et al., 1971b).

Polar Cap Interior. The process responsible for the unusual brightness of highstanding features (crater rims, central peaks, or isolated knobs) relative to the surrounding surface, especially crater bottoms and etch pits, may be the textural differentiation of the CO₂ frost cover experiencing a more intense history of sublimation and condensation under the local meteorological conditions (Sharp et al., 1971). Also, adiabatic compression (heating) and expansion (cooling) of the CO₂ Martian air blowing over features of strong relief may result in sublimation of low-lying CO₂-frost and condensation over high areas (see Leighton et al., 1971).

The etch features (pits and furrows), which are depressions carved into the frost cover, with irregular, angular shapes, are quite unique to the cap interior and seem to be the result of either (1) differential ablation caused by local thin accumulations of dark debris (dust) blown in at one time--which would explain their lesser reflectivity--or (2) wind erosion "which can scour and pluck in unusual fashion" Again to quote Sharp et al. (1971b): "the sharpness and angularity of etch features suggest undermining of a frost layer with a slabby structure."

The beaded lineations and other smaller features seem to have been shaped by wind motion, that is by scour and drifting of the frost. "Fine detail on larger crater rims resembles scalloping and fluting by wind scour. Much of the pole cap surface looks swept because of faint lineations and elongation of minor features, possibly produced through scour and drifting by wind" (Sharp et al., 1971b).

Central Polar Region. The remarkable long, quasi-linear markings definitely are ground features and not clouds, but their origin is mysterious. From the photography, it is not clear whether they are troughs, ridges, or scarps. They do resemble our longitudinal dunes, but are on a much larger scale and more irregular. If they are ridges, they may also represent accumulations of snow or ice, and/or rock material, suggesting large

moraines. If they are considered like scarps, then they conceivably could be "the edges of platy layers of remnant ice" (Sharp et al., 1971b). These authors speculate that great masses of perennial ice may have accumulated under a more favorable phase of the effective precessional cycle of 50,000 years,* and that this has occurred repeatedly for the south polar region. Perhaps the unusual brightness of the central polar region, the paucity and faintness of craters, and the quasi-linear markings are the result of a cumulative effect of alternate large and small remnant summer central caps over many millions of years.

Thickness of Frost Cover

The frost cover is thin in the marginal zone, but becomes much thicker in the cap interior with increasing latitude. However, the thickness is obviously quite variable in the interior, locally because some large craters are partly buried while elsewhere many small ones (1 km across) do show their presence. Such variations probably are due to drifting and piling up of the frost by wind. The thickness of these accumulations appears to be "on the order of tens of meters" (Sharp et al., 1971b). On the other hand, the etch pits of large size (such as the "elephant's footprint" in 7N14) are negative relief features suggesting thicknesses "of at least tens-of-meters." They may, however, not be due to differential ablation.

These thicknesses inferred from Mariner 7 photography of the South Polar Cap appear to be roughly in agreement with the theoretically estimated average thicknesses (about a meter) obtained by Leighton and Murray (1966), and Cross (1971b).**

Permanence of Frost or Ice

Sharp et al. (1971b) speculate from quantitative estimates of the total mass of solid CO₂ possibly involved in the Martian polar caps through either the annual or precessional cycles, that most likely there are sizable local masses of old "dirty" perennial CO₂ deposits which in summer escape detection under an insulating blanket of dust at least a few centimeters thick. The etch-pits and quasi-linear markings may be indications of such deposits. The Mariner 1971 mission might find evidence of their permanence.

*The ~50,000 year effective precessional cycle is the result of the combined effects of the rate of advance of the perihelion (or line of nodes) and the rate of regression of the north pole of rotation (or line of equinoxes or solstices) - see Section 1 on Orbital and Physical Data.

**Cross (1971b) made approximate calculations of the seasonal variations in size and average thickness of both polar caps. He found that the Spring Southern Cap is not only larger but one-fifth thicker than the Northern one (disregarding the perennial CO₂ cap deposits).

The total mass of solid CO₂ estimated to be present now is either

- 1) Between ~ 10 and $\sim 100 \text{ g cm}^{-2}$ (average over planet). In this case, a perennial CO₂ frost cap normally exists at one pole, alternating from S to N through the 50,000-year precessional cycle. Local perennial deposits may occur at both poles as a result of wind drifting and/or dust blanketing.
- or:
- 2) Greater than $\sim 100 \text{ g cm}^{-2}$. In this case both poles harbor perennial CO₂ caps, and large masses of CO₂ might exist under dust blankets.

3.5.5 DARK AND BRIGHT AREAS (MERIDIANI SINUS REGION): BOUNDARIES AND MARKINGS

Near their closest approach in 1969, both Mariners photographically sampled one of the prominent, stable dark areas of Mars: Meridiani Sinus (well-known by its forked shape) and the appending arm of Sabaeus Sinus. Mariner 6 picture quality and resolution were especially high (see 6N11, 13, 7N4, 6, and 8). Thus it was possible for the CIT geologists (Cutts et al., 1971) to make a special analysis of this dark area and its immediately surrounding light areas. Their results are presented below.

Morphologically, this complex dark area, Meridiani Sinus-Sabaeus Sinus, displayed around its periphery three types of boundaries:

- 1) Linear boundary, characterized by dark streaks within the light area and nearly parallel to the overall boundary trend. This is seen between Sabaeus Sinus and adjacent Moab light area.
- 2) Transverse boundary, characterized by projections perpendicular to, or at steep angle to, the overall boundary trend with some dark "outliers" in the light area. This is seen on the eastern boundary of Meridiani Sinus next to light area Edom, which is a large crater.
- 3) Diffuse boundary, characterized by a gradual transition in albedo. This is seen on the western boundary of Meridiani Sinus next to light area Thymiamata, and continues along the southern boundary next to light area Deucalionis Regio.

The character of the boundary may be controlled by the local topography. Along crater walls (e.g., Edom) and scarps, the boundary is sharp with light material on the lower side; the dark area then shows uniform albedo, while the light area usually varies in albedo. In regions lacking relief the boundary is diffuse, as near Deucalionis Regio. However, between Sabaeus Sinus and Deucalionis Regio there are many short linear depressions nearly parallel to the main diffuse boundary trend and which disappear gradually into the light area.

Cratered terrain extends over Meridiani Sinus and surrounding light areas, with no apparent change in density and morphology of the large flat-bottomed craters, except in the northern light areas, where craters are fewer and more subdued.

Some craters in Meridiani Sinus display unusual albedo markings: crescents of high albedo are on the northern part of crater floors and southern slopes of crater walls and rims. Since this is contrary to the effects of solar illumination, it was suggested by Cutts et al. (1971) that this may indicate aeolian transport of "light material" in or out of the craters.

3.5.6 CANALS AND LINEAMENTS

Canals

The three Mariners have not confirmed the presence of the classical system of canals. Instead, only a few linear formations and irregularly elongated dark patches could be detected. The Mariner 4 TV track, which, it was argued at the time, did not cross many prominent canals, apparently revealed some dark bands and linear (tectonic) structures in frames 4N1-3. These markings were "recognized" by Katterfeld and Hettervari (1969) in particular as being portions of the large canals Erebus and Orcus. (Others, less distinct, in 4N1 were interpreted as belonging to the canals Hades and Boreas.) But this was not clear to most other geologists. The Mariner 6 and 7 TV NE tracks did cross prominent equatorial canals, but nothing very convincing has been seen. (Note: Many so-called "lineaments" were detected, but, as defined below, the term lineaments refers to much smaller and narrower markings which cannot be identified as canals.) The FE pictures which covered the planet at higher than telescopic resolutions showed only very few dark elongated markings which could approximate in form the canals presumed to exist at their locations. Such were the wide dark peninsula Coprates and the elongated island Cerberus, both called "canals" on pre-Mariner maps. Besides these two important examples (which correspond to wide canals seen at the telescope), there were reports by Leighton et al. (1971b) of quasi-linear alignments of dark-floored craters (at the position of the canal Gehon, for example) and also mention by Cutts et al. (1971) of much more subtle boundary lines between differently toned bright areas (north of Meridiani Sinus), which appear to be contrast effects. It is possible that morphological features, other dark patches and craters will later be found associated with other canals, but this remains to be seen.

In summary, the present evidence supporting the existence of "canals" is therefore unsubstantial. So far, the canals cannot be identified as a distinct physiographic unit on Mars surface. (Note: It was argued that the season on Mars at the time of the 1969 flybys was improper for the canals to show up at greatest contrast since the canals supposedly follow the wave of darkening, and are darkest in late spring-summer. This argument is expected to be answered during the Mariner 9 surveillance of the planet's variable surface features.)

Lineaments

It is now known from Mariner photographs that there exist on the surface of Mars structural linear features interpreted as faults, grabens, horsts, fractures, ridges, rilles, valleys, crater chains, etc. Some of these "lineaments" may be considered to be lines of weakness in the Martian crust and

serve to indicate zones of past, and possibly present, tectonic activity (crustal deformation processes). Many Martian lineaments have already been mapped on the Mariner NE photographs. By plotting direction and frequency of the lineaments in polar coordinates (as radius vector), one can produce an azimuthal frequency diagram, more commonly called "rose diagram," for a certain region, or a group of regions, and eventually for the whole planet. Figures 29 and 30 illustrate examples of regional rose diagrams: one was issued by Katterfeld (1969) from mapping of lineaments on Mariner 4 frames 4N3-15; the other is by Binder (1971) from mapping on a number of Mariner 4, 6, and 7 frames. These diagrams often exhibit clearly the prevailing trends or directions of regional tectonism or crustal instability. For example, Katterfeld's diagram shows strong prevalent NW-SE and NE-SW directions and weak N-S and E-W directions. Generalization to the whole planet at present, however (as done by Wells, 1969),* appears premature until near-global NE photographic coverage by spacecraft has been achieved.

Oases

The oases, usually recorded on early maps as round or oval dark spots at the intersection of canals in bright areas, were seen by Mariners 6 and 7 to have irregular shapes (as observed in more recent telescopic observations) and to resolve into fine structure, where "circular and annular markings may correspond to large individual craters" (Cutts et al., 1971). See for example Oxia Palus in 7N5. Possibly a smaller oasis is formed by a single large crater. Hartmann(1971b) hypothesized that the darkness of the oases, considered as impact craters, can be accounted for (in his model of aeolian crater obliteration) by "dark rocky ejecta of bedrock deposited on top of a thin veneer of desert material."

*Wells (1969) inferred the existence over the Martian globe of these two overlapping grid systems from Katterfeld's regional diagram and a more global diagram based on the orientation of canals. (1969 References: see Wells, 1971 b)

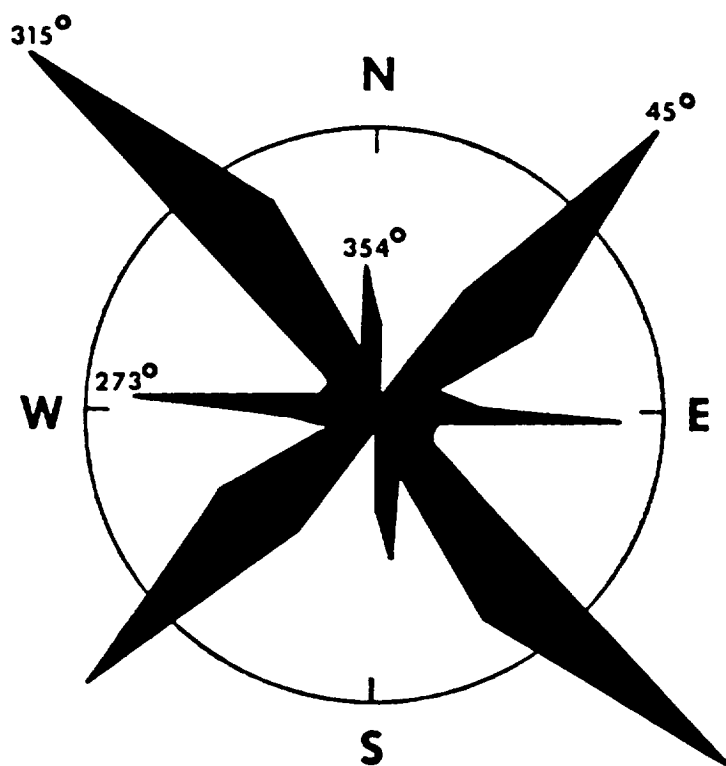


Fig. 29. Rose diagram showing the azimuthal distribution of 868 lineaments mapped from the Mariner 4 photographs 4N3-15 (Katterfeld (1969) modified by Wells, 1971 b).

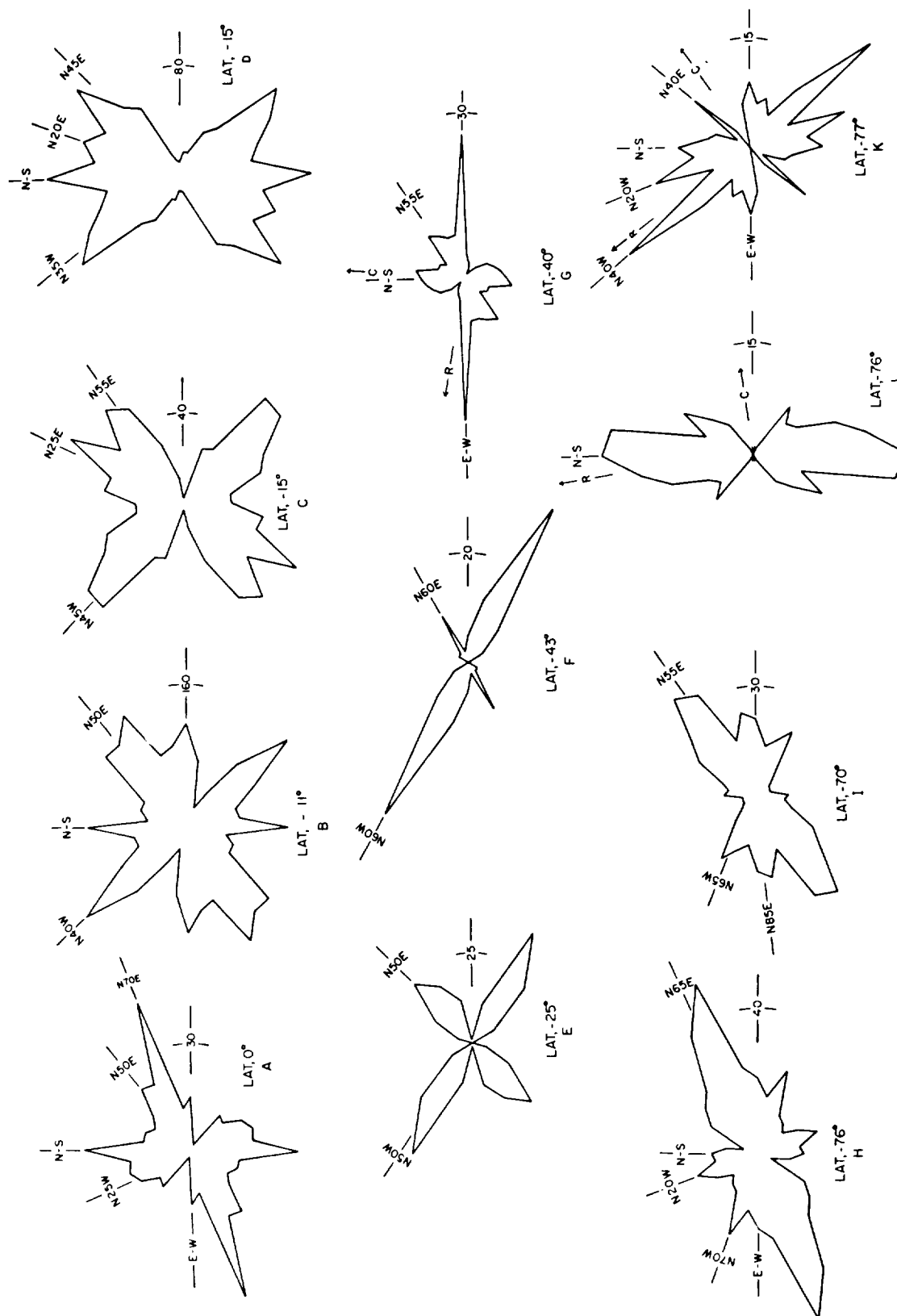


Fig. 30. Rose diagrams of Martian lineaments at several latitudes, mapped from Mariner 4, 6, and 7 photographs (Binder, 1971, private communication).

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A mosaic of the Mariner IV pictures superimposed upon a photograph of a hand-painted model of Mars. Picture 1 caught the limb, or edge, of the planet as Mariner IV observed it from a position about 8,000 miles below the plane of Mars' orbit at a slant range of 10,500 miles. As the spacecraft swept under the planet, the television scan path progressed toward the southeast and in picture 19 moved across the terminator (the light-dark boundary). The last three pictures (20, 21, and 22) were taken in complete darkness.

July 1, 1968

FOLDOUT FRAME /



photograph of a hand-painted planet as Mariner IV
 line of Mars' orbit at a slant
 planet, the television scan
 ed across the terminator
 and 22) were taken in



Picture 7

Picture 7 is wholly within the south-eastern part of the bright region Zephyria, near Mare Sirenum.

Location of picture center:

Latitude.....-13°

Longitude 174°

Dimensions of area:

East-west.....290 km (180 mi)

North-south 290 km (180 mi)

Spacecraft distances:

Altitude.....13,192 km
 (8,179 mi)

Slant range 13,582 km
 (8,421 mi)

Time and lighting:

Local time about noon

Phase angle 59.6° to 60.5°

Zenith angle Sun is 29° north
 of the zenith

Filter green

Overlap.....Lower right corner
 overlaps picture 8

Time of exposure ... 00:25:45 GMT,
 July 15, 1965



Picture 8

Picture 8 contains part of the bright region Zephyria and the dark Mare Sirenum. The border between these two regions trends across the middle of the picture.

Location of picture center:

Latitude.....

Longitude 174°

Dimensions of area:

East-west.....290 km (180 mi)

North-south 290 km (180 mi)

Spacecraft distances:

Altitude.....

Slant range 13,582 km (8,421 mi)

Time and lighting:

Local time about noon

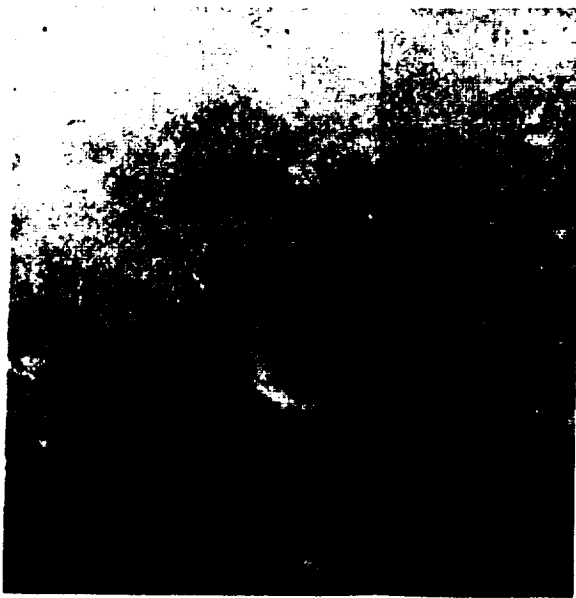
Phase angle 59.6° to 60.5°

Zenith angle Sun is 29° north of the zenith

Filter green

Overlap.....Upper right corner overlaps picture 7

Time of exposure ... 00:25:45 GMT,
 July 15, 1965



Picture 8

Picture 8 contains part of Zephyria and the dark Mare Sirenum. The border between these two features trends across the middle of the picture.

Location of picture center:

Latitude.....-17°
Longitude 173°

Dimensions of area:

East-west 290 km (180 mi)
North-south 275 km (170 mi)

Spacecraft distances:

Altitude 13,056 km
(8,095 mi)
Slant range 13,373 km
(8,291 mi)

Time and lighting:

Local time about noon
Phase angle 59.5° to 60.5°
Zenith angle Sun is 32° north
of the zenith

Filter orange

Overlap.....Upper left corner
overlaps picture 7

Time of exposure ... 00:26:33 GMT,
July 15, 1965



Picture 9

Picture 9 is largely in the dark area Mare Sirenum, bordering on the light area Atlantis in the southwest corner of the picture.

Location of picture center:

Latitude.....-24°
Longitude 169°

Dimensions of area:

East-west 275 km (170 mi)
North-south 260 km (161 mi)

Spacecraft distances:

Altitude 12,790 km
(7,930 mi)
Slant range 13,004 km
(8,062 mi)

Time and lighting:

Local time about noon
Phase angle 59.4° to 60.4°
Zenith angle Sun is 39° from
the zenith

Filter orange

Overlap.....Lower right corner
overlaps picture 10

Time of exposure ... 00:28:09 GMT,
July 15, 1965



Picture 10 is
Mare Sirenum
light area At
on Mare Sire
corner of the

Location of p

Latitude..
Longitude

Dimensions o

East-west
North-sou

Spacecraft di

Altitude ..

Slant rang

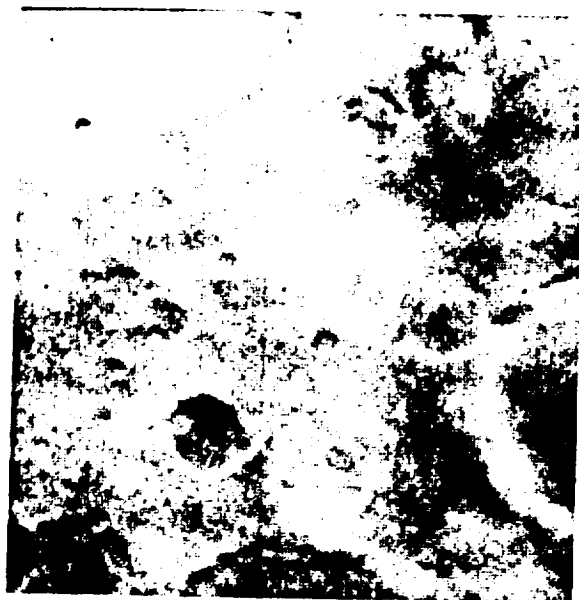
Time and ligh

Local time
Phase ang
Zenith ang

Filter

Overlap.....

Time of expo



Picture 10

e dark area
g on the
southwest

Picture 10 is partly in the dark area Mare Sirenum, and largely in the light area Atlantis, which borders on Mare Sirenum in the northeast corner of the picture.

r:
.....-24°
.....169°

Location of picture center:
Latitude.....-27°
Longitude 167°

m (170 mi)
m (161 mi)

Dimensions of area:
East-west 275 km (170 mi)
North-south 260 km (161 mi)

12,790 km
(7,930 mi)
13,004 km
(8,062 mi)

Spacecraft distances:
Altitude 12,660 km
(7,849 mi)
Slant range 12,843 km
(7,963 mi)

about noon
° to 60.4°
39° from
the zenith

Time and lighting:
Local time about noon
Phase angle 59.4° to 60.3°
Zenith angle Sun is 42° from
the zenith

.. orange

Filter green

ght corner
picture 10

Overlap.....Upper left corner
overlaps picture 9

:09 GMT,
15, 1965

Time of exposure... 00:28:57 GMT,
July 15, 1965



Picture 11

Picture 11 probably is principally within the dark Mare Sirenum, but may be in or near the lighter area Atlantis between Mare Sirenum and Mare Cimmerium.

Location of picture center:
Latitude.....-33°
Longitude 162°

Dimensions of area:
East-west 275 km (170 mi)
North-south 240 km (149 mi)

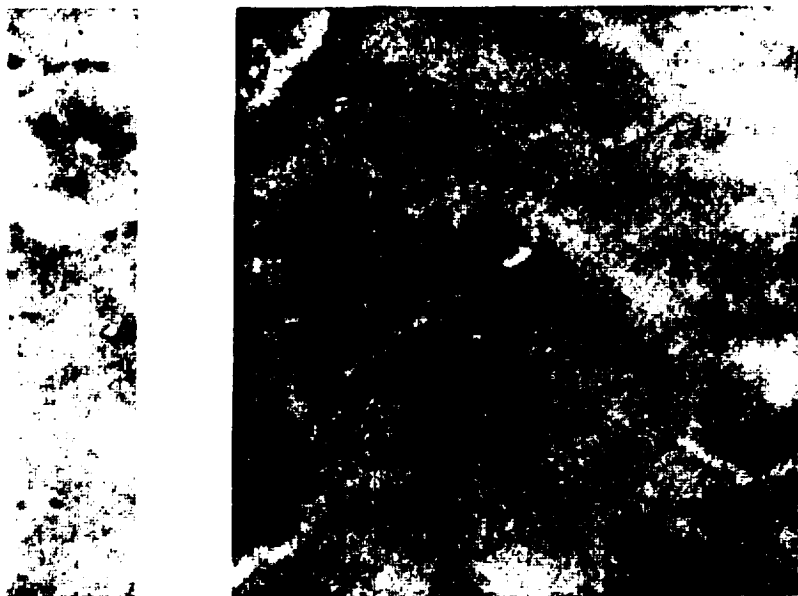
Spacecraft distances:
Altitude 12,407 km
(7,692 mi)
Slant range 12,564 km
(7,790 mi)

Time and lighting:
Local time about 12:40
Phase angle 59.3° to 60.3°
Zenith angle Sun is 49° from
the zenith

Filter green

Overlap.....Lower right corner
overlaps picture 12

Time of exposure... 00:30:33 GMT,
July 15, 1965



Picture 12

Picture 12 probably lies across the poorly defined border between the dark Mare Sirenum and the lighter area Atlantis.

Location of picture center:

Latitude.....-36°

Longitude 160°

Dimensions of area:

East-west 275 km (170 mi)

North-south 240 km (149 mi)

Spacecraft distances:

Altitude 12,284 km

(7,616 mi)

Slant range 12,446 km

(7,717 mi)

Time and lighting:

Local time about 12:40

Phase angle 59.3° to 60.2°

Zenith angle Sun is 52° from
the zenith

Filter orange

Overlap.....Upper left corner
overlaps picture 11

Time of exposure... 00:31:21 GMT,
July 15, 1965

Fig. 24. Mariner IV pictures 7 to 12, and the locations of Martian regions photographed in pictures 1 to 19. North is at the top.

3.6 MARINER 1969 PHOTOGRAPHIC ATLAS OF MARS

INTRODUCTION

The successful flybys of Mariners 6 and 7 past Mars, on July 31 and August 5, 1969, respectively, have provided more than 200 complete television pictures of the planet which have significantly increased our knowledge of its surface and atmosphere. The volume and quality of the data returned greatly surpassed that obtained from the initial flyby of Mariner 4 in 1965. Not only was the whole planet photographed during several rotations, but many high-resolution closeup photos were obtained over its Southern Hemisphere which had just entered its spring season. It is the purpose of this section to present the pictorial highlights of the 1969 Television Imaging Experiment results. The selected pictures presented here, with relevant photographic and areographic information, are often referred to and discussed in other sections of this document. The complete set of pictures will be published in book form as a NASA SP-263, under the title "The Mariner 6 and 7 Pictures of Mars" (Collins, 1971), and may more properly be called a "photographic atlas."

TELEVISION EXPERIMENT DESIGN

The television observations period for each spacecraft during the Mars encounter was divided according to two periods:* (1) a two to three day far encounter (FE) period terminating several hours before actual closest approach of the planet, and (2) a half-hour near encounter (NE) period centered on closest approach.

The scan platform of both spacecraft carried two cameras of different focal lengths, providing two resolutions differing by a factor of ten. The short focal length or wide-angle camera (camera A), for the lower resolution, was equipped with a rotating set of four filters sequenced red, green, blue, and green, on a filter wheel. The long focal length or narrow-angle camera (camera B), for the higher resolution, had only one blue cutoff (or yellow haze) filter. The characteristics of the camera optics are contained in Table 1 and the transmission curves of the filters utilized are shown in Figs. 1, 2, and 3. A full description of the optics and filters may be found in Montgomery and Adams (1970), and Danielson and Montgomery (1971).

The FE pictures were taken with camera B to obtain highest resolution of the disk. The NE pictures were taken alternatively with cameras A and B so that a (high resolution) B frame was nested within the overlapping region of two successive (low resolution) A frames. The camera A frames were taken successively through the alternate filter sequence indicated above, starting with blue for Frame No. 1. All B frames were taken through the unique yellow haze filter.

*With Mariner 7, an additional, originally unscheduled, period of observations took place between the FE and NE periods. During this late far encounter period (LFE) an additional 88 valuable pictures were secured through the two cameras.

Table 1. Characteristics of the Mariner 6 and 7 Camera Optics.

	Camera A (wide-angle)	Camera B (narrow-angle)
Type	Zeiss Planar f/2 multielement lens stopped down to f/5.6	Modified Schmidt- Cassegrain telescope f/2.4
Focal Length	52 mm	508 mm
Field of View	11° × 14°	1.1° × 1.4°
Aperture	10 mm	200 mm
Shutter	4-position rotary	2-blade, right-left
Filters (effective wavelength)	Red (5730 Å) Green (5260 Å) Blue (4690 Å)	Blue cut-off (5600 Å) (Schott GC-14 glass)
Exposure Time (fast, slow)	90 and 180 msec	6 and 12 msec

DANIELSON AND MONTGOMERY

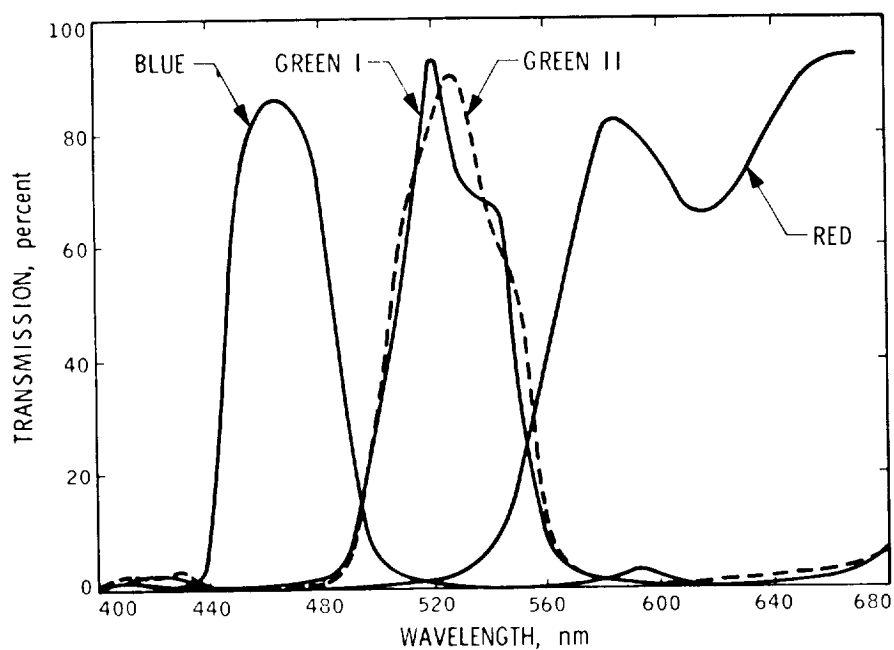


Fig. 1. Spectral transmission, Mariner 6 camera A filters. Spectral response characteristics of each filter incorporated in the A camera flown on Mariner 6.

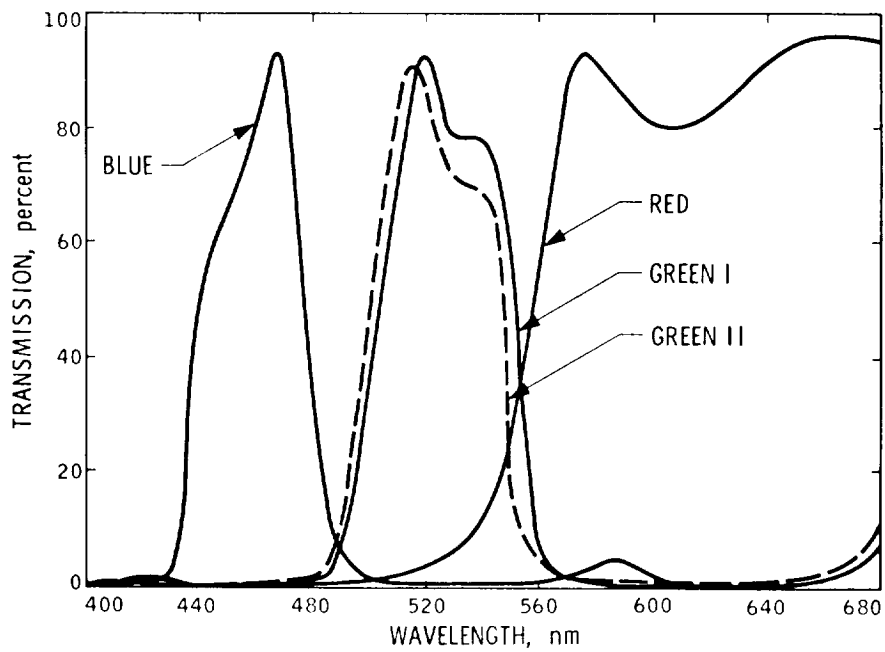


Fig. 2. Spectral transmission, Mariner 7 camera A filters. Spectral response characteristics of each filter incorporated in the A camera flown on Mariner 7.

Danielson and Montgomery (1971)

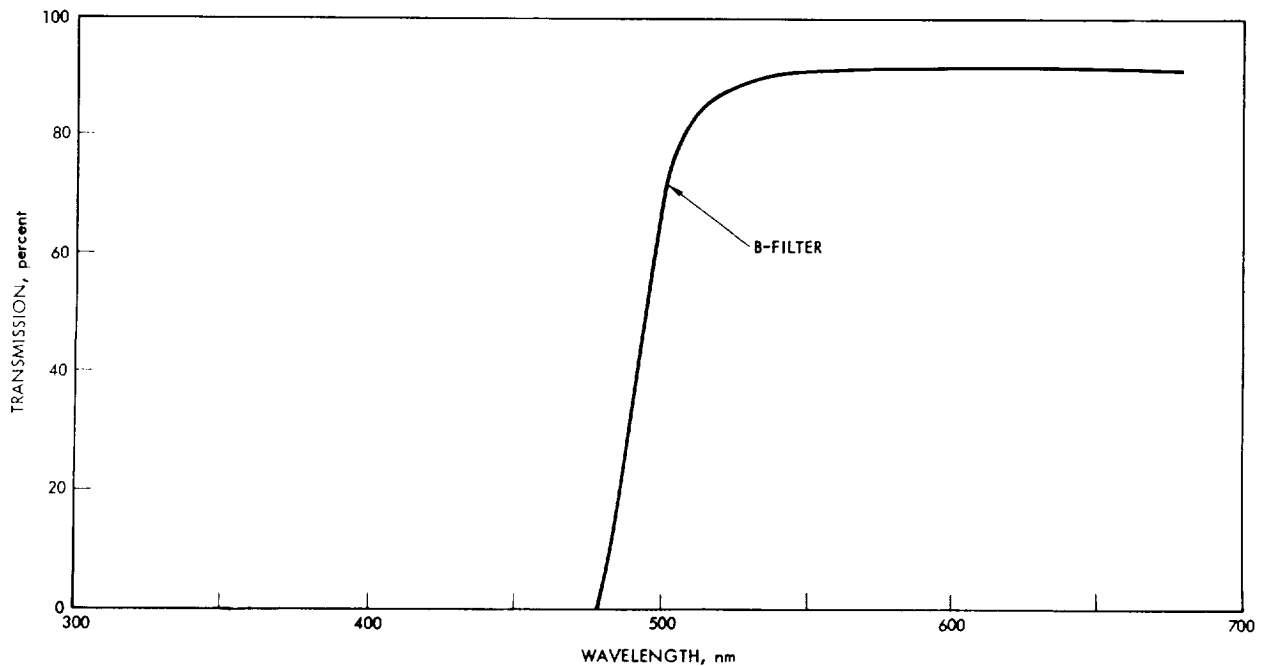


Fig. 3. Transmission characteristics as a function of wavelength for the camera B filter.

The designation of each frame is identified by a code which cites spacecraft number (6 or 7), sequence letter (F or N) and frame sequence number. For example, 6N3 is decoded as: 6 = Mariner 6, N = near encounter, 3 = frame number 3. All odd-numbered, near encounter frames were taken by camera A (low resolution) and all even-numbered frames by camera B (high resolution).

CAMERA SYSTEM

The Television Camera System was composed of a vidicon image tube, complex analog-to-digital conversion assembly, and a magnetic tape recorder system for recording both analog and digital video data prior to transmission to Earth. This system was designed to improve the visual contrast of the Martian surface,* as well as maximize the transmission of both TV data and other scientific data obtained by the Mariners. The onboard video processing is described in detail by Danielson and Montgomery (1971). Essentially, each camera scanned a raster of 945 picture elements (or pixels) per line and 704 lines per frame, so that a complete picture consisted of 665,280 pixels. Each pixel's brightness was digitized (encoded) into an 8-bit binary word, providing 256 ($=2^8$) possible levels of brightness or shades of gray to be recorded. The onboard encoding was accomplished, however, in three versions:

- 1) A composite analog video (CAV) picture, consisting of a fully sampled raster, with each pixel encoded to 6 significant bits. Before encoding, the analog signal from the vidicon was modified so as to emphasize low-contrast detail; this was done through two amplifiers: an "automatic gain control" (AGC) which enhanced the visibility of the small-scale detail, and a "cuber" which enhanced the local contrast (by a factor of ~ 3). After encoding, the data was recorded on tape.
- 2) An "every seventh" spacing digital video (DV) picture, consisting of sampling every seventh pixel along each scan line, with encoding to 8 significant bits.**
- 3) An "every-twenty-eighth" (ETE) spacing digital picture, from sampling every 28th pixel along each scan line, with encoding to 6 significant bits.**

The encoding scheme used in versions 2) and 3) permitted transmission of both the nonvideo science data (forming a "data bar" in the middle of the DV pictures) and information on the nonlinearity of the AGC and cubing amplifiers.

IMAGE PROCESSING

The image processing performed at the JPL Image Processing Laboratory was designed to give two final products or versions of the images: (1) maximum discriminability version ("Max-D"), and (2) photometric version.

*Mariner 4 revealed very low contrast factor.

**With the two most significant bits truncated.

The Max-D version strongly emphasizes the fine-scale brightness variations and, therefore, local abrupt contrasts of small surface features, while sacrificing true contrasts between large surface areas. This effect is due to the AGC-cuber combination, which acts as a photometric high-pass filter, eliminating the slow, low-frequency variations of brightness (see Dunne et al., 1971). Only the NE pictures were processed in the Max-D version.

The photometric version gives a large-scale true brightness (or 'photometric') representation of the surface albedo differences. This version is useful for study of the classical dark areas/bright areas dichotomy or albedo patterns of large areas of the planet. All the FE pictures were processed in this version only.

To obtain the Max-D versions, the following processing was performed on the CAV picture streams:

- 1) Rectification or correction to remove the various distortions due to the vidicon system. These distortions include system noises of several kinds: periodic noise producing a basket-weave pattern, long-line or streak noise, and isolated (black and white) spike noise.
- 2) Enhancement of frequency response to compensate for modulation transfer function fall-off.
- 3) Geometric distortion correction to remove optical and especially electronic imaging aberrations. (Note: The geometric distortion here is not the projection distortion due to oblique viewing.)

To obtain photometric versions, the processing necessitated first performing a reconstruction task of a "full analog video" (FAV) picture (that is, a picture as could be obtained at the vidicon before the AGC and cuber). This task consisted of two parts:

- 1) Restoration of the 'most significant bits' truncated before transmission, in the DV and ETE picture data streams.
- 2) Reconstruction proper of a full picture, from recombination of the three picture data streams (CAV, DV, and ETE).

This included a correction to remove the nonlinear photometric effects of the AGC-cuber combination.

Then, the same rectification processing, as done for the Max-D version, was performed; that is, correction of distortions due to the vidicon system (and in addition the removal of the 'residual image'), and correction of geometric distortions.

Finally, a photometric decalibration was performed to remove shading and light-sensitivity variations due to the vidicon (nonlinear and spatially varying sensitivity properties). A discussion of the JPL image processing techniques applied to the Mariner 6 and 7 pictures has been given by Rindfleisch et al., (1971).

3.6.1 FAR ENCOUNTER

Introduction

All the far encounter (FE) pictures were taken with the narrow-angle camera (B) to obtain highest possible resolution. Mariner 6 took a total of 49 FE pictures in two series, extending over almost two days and two rotations of Mars. The Mariner 7 camera was activated a day earlier and produced a total of 91 FE pictures in three series, covering three complete rotations of the planet.

Only the most significant pictures are presented here, starting with the initial photo at 1.7 million km and concluding with the closest FE photo taken at 130,000 km from Mars. The terrestrial date and the longitude of the central meridian on the Martian disk are indicated below each photograph. When the full disk is seen, a fixed size is used for the image of the disk. Later, as the spacecraft's TV field of view is reduced to a portion of the disk, we present the picture as it was received. The first series of pictures obtained by Mariner 7 does not show much more than was previously known from Earth telescopic observations, because of the low resolution. As the spacecraft approached closer to the surface of Mars, as shown in the second series of Mariner 7 or first series of Mariner 6 photos, the improving resolution revealed many of the classical surface feature aspects not previously observable. As the spacecraft approached 300,000 km from the planet a wealth of detail began to appear.

In presenting this brief photographic reconnaissance of Mars by the two spacecraft of 1969, it will be seen that many previous opinions and speculations concerning the true nature of the surface of Mars, and associated atmospheric phenomena, have had to be revised. Only the highlights of the FE sequence are shown and annotated in the photos contained herein.

The two spacecraft approached Mars slightly south of its equatorial plane: 6 degrees offset for Mariner 6, and 4 degrees for Mariner 7. Consequently, the cameras viewed the entire Martian globe except for a small zone centered on the north pole (see Fig. 4). The Martian surface features, therefore, 'drifted' on flattened elliptical paths across the disk.

The classical westward increasing system of longitudes is used (0 to 360 degrees) in denoting position on Mars. The present zero meridian passes about 3 degrees west of Fastigium Aryn (the old origin of longitudes, located inside the fork of Meridiani Sinus).

The trajectory of the spacecraft was such that Mars was photographed in the FE sequence with a noticeable solar phase angle of about 22 degrees. The dark crescent beyond the morning terminator appeared on the left side of all the pictures, which are oriented with the Martian north pole at the top. Since the direction of rotation for Mars is the same as for the Earth, the surface features will appear to drift from west to east, that is from left to right, as the Mariners approached the planet.

The planetary photography data pertaining to each of the 140 FE pictures taken are listed in Table 2, Far Encounter Photoreference Data.

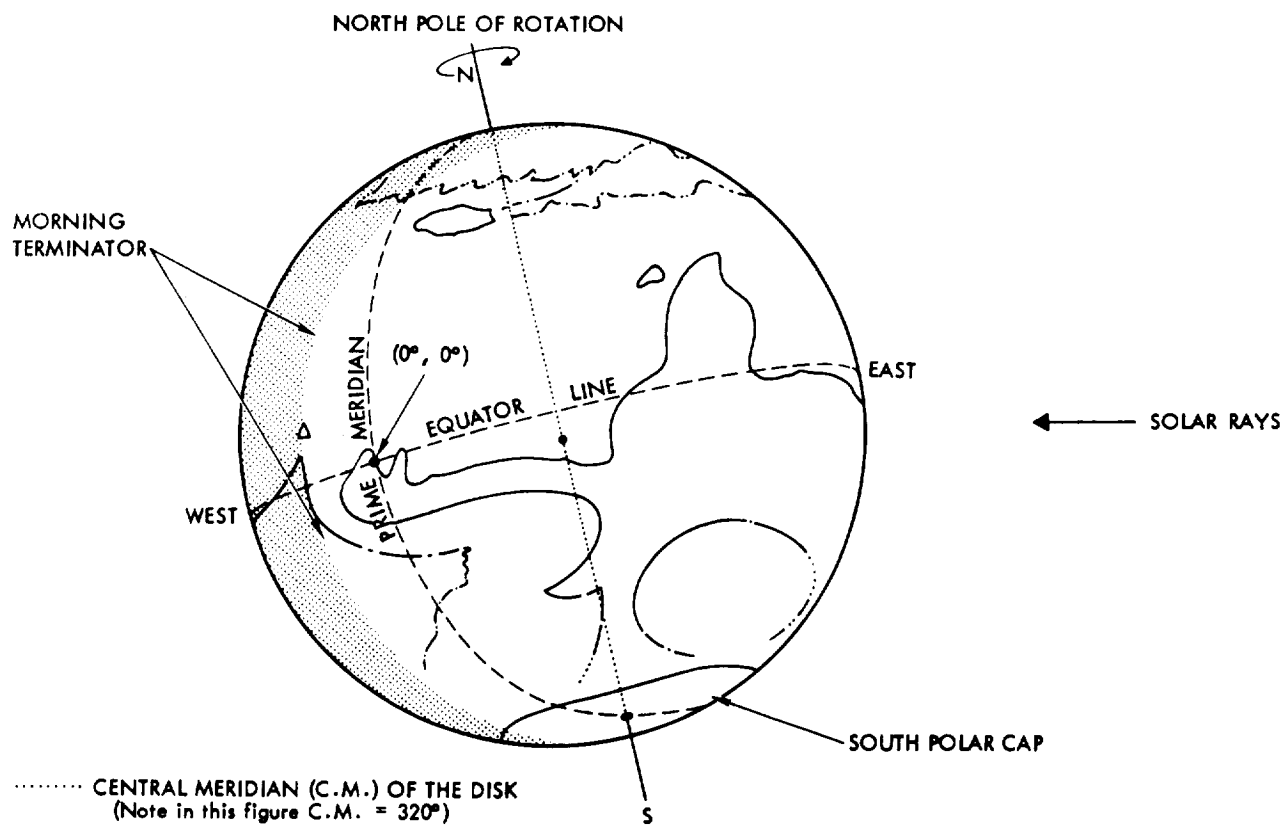


Fig. 4. The globe of Mars.

Table 2. Far encounter photoreference data.

Picture Number	Date	Shutter	Range, km	Phase Angle, deg	Center of Disk		Resolution km/Pixel
					Longitude, deg	Latitude, deg	
Mariner 6							
6F1	July 29 ↑ ↓ July 29 ↓ July 30 ↑ ↓ July 30	Bottom	1,244,221	21	100°W	-6	34.0
6F2		Bottom	1,228,388	21	109	-6	33.4
6F3		Bottom	1,212,556	21	117	-6	32.9
6F4		Bottom	1,196,724	21	126	-6	32.5
6F5		Top	1,180,281	21	136	-6	32.1
6F6		Top	1,164,448	21	145	-6	31.7
6F7		Top	1,148,615	21	153	-6	31.3
6F8		Top	1,132,782	21	162	-6	30.8
6F9		Bottom	1,116,342	21	172	-6	30.4
6F10		Bottom	1,100,507	21	181	-6	30.0
6F11		Bottom	1,083,790	21	190	-6	29.5
6F12		Top	1,068,232	21	199	-6	29.0
6F13		Top	1,052,399	21	208	-6	28.6
6F14		Top	1,036,568	21	217	-6	28.2
6F15		Top	1,020,733	21	226	-6	27.8
6F16		Bottom	1,004,291	21	235	-6	27.3
6F17		Bottom	988,457	21	244	-6	26.8
6F18		Bottom	972,624	21	253	-6	26.4
6F19		Top	956,181	21	262	-6	26.0
6F20		Top	940,347	21	271	-6	25.6
6F21		Top	924,514	21	280	-6	25.2
6F22		Top	908,679	21	289	-6	24.7
6F23		Bottom	892,236	21	298	-6	24.3
6F24		Bottom	876,402	21	307	-6	23.8
6F25		Bottom	860,568	21	316	-6	23.4
6F26		Bottom	844,733	21	325	-6	23.0
6F27		Top	828,289	21	334	-6	22.6
6F28		Top	812,455	21	343	-6	22.1
6F29		Top	796,619	21	352	-6	21.7
6F30		Bottom	780,175	21	1	-6	21.2
6F31	Bottom	764,339	21	10	-6	20.8	
6F32	July 30 ↑ ↓ July 31 						

Table 2. Far encounter photoreference data (continued).

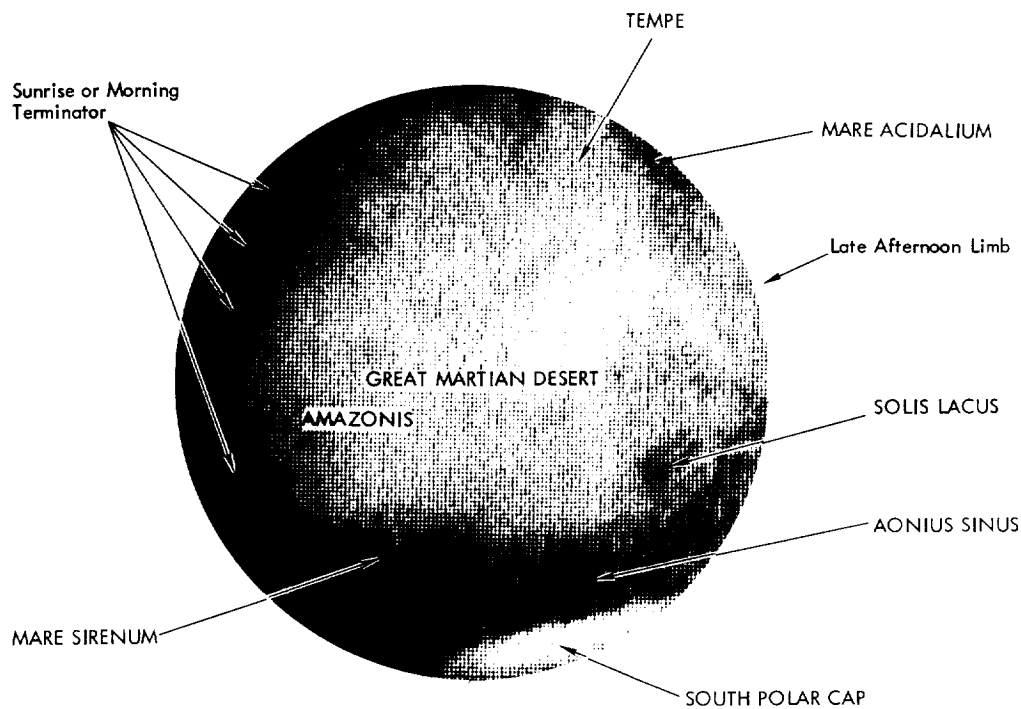
Picture Number	Date	Shutter	Range, km	Phase Angle, deg	Center of Disk		Resolution km/Pixel
					Longitude, deg	Latitude, deg	
Mariner 7 (continued)							
7F13	Aug 2 ↑	Bottom	1,582,971	22	199°W	-4	43.2
7F14		Top	1,571,621	22	206	-4	42.9
7F15		Top	1,559,673	22	213	-4	42.5
7F16		Bottom	1,548,323	22	219	-4	42.2
7F17		Top	1,536,973	22	226	-4	41.9
7F18		Bottom	1,525,623	22	233	-4	41.6
7F19		Top	1,514,167	22	239	-4	41.3
7F20		Bottom	1,502,923	22	246	-4	41.0
7F21		Bottom	1,490,977	22	252	-4	40.7
7F22		Top	1,479,626	22	259	-4	40.4
7F23		Bottom	1,468,279	22	265	-4	40.1
7F24		Top	1,453,533	22	272	-4	39.8
7F25		Bottom	1,445,577	22	278	-4	39.4
7F26		Top	1,433,630	22	285	-4	39.1
7F27	Top	1,422,281	22	292	-4	38.8	
7F28	Bottom	1,410,931	22	298	-4	38.5	
7F29	Top	1,399,581	22	305	-4	38.2	
7F30	Bottom	1,388,233	22	311	-4	37.9	
7F31	Top	1,376,882	22	318	-4	37.6	
7F32	Top	1,364,937	22	325	-4	37.3	
7F33	Aug 2 ↓	Bottom	1,353,586	22	331	-4	37.0
7F35	Aug 3 ↑	Bottom	1,199,474	23	60	-4	32.8
7F36		Top	1,184,540	23	68	-4	32.4
7F37		Top	1,169,009	23	77	-4	31.9
7F38		Bottom	1,154,076	22	86	-4	31.5
7F39		Bottom	1,138,545	22	95	-4	31.1
7F40		Top	1,123,613	23	103	-4	30.7
7F41		Top	1,108,081	23	112	-4	30.3
7F42		Top	1,092,551	23	121	-4	29.9
7F43		Bottom	1,077,617	23	130	-4	29.5
7F44		Bottom	1,062,086	23	139	-4	29.0
7F45		Top	1,047,152	23	147	-4	28.6
7F46		Top	1,031,621	23	156	-4	28.2
7F47		Bottom	1,016,687	23	165	-4	27.8
7F48		Bottom	1,001,156	23	174	-4	27.3
7F49	Bottom	985,625	23	183	-4	26.9	
7F50	Top	970,691	23	191	-4	26.5	
7F51	Top	955,160	23	200	-4	26.1	
7F52	Bottom	940,225	23	209	-4	25.7	
7F53	Bottom	924,693	23	218	-4	25.3	
7F54	Top	909,759	23	226	-4	24.8	
7F55	Top	894,227	23	235	-4	24.4	
7F56	Top	878,695	23	244	-4	24.0	
7F57	Bottom	863,760	23	253	-4	23.6	
7F58	Bottom	848,227	23	261	-4	23.2	
7F59	Top	833,292	23	270	-4	22.8	
7F60	Top	817,760	23	279	-4	22.4	
7F61	Bottom	803,248	23	287	-4	22.0	
7F62	Bottom	787,291	23	296	-4	21.5	
7F63	Top	772,355	23	305	-4	21.1	
7F64	Aug 3 ↓	Top	756,821	23	314	-4	20.7
7F65	Aug 4 ↑	Top	741,287	23	323	-4	20.3
7F66		Bottom	726,351	23	331	-4	19.9
7F67		Bottom	710,816	23	340	-4	19.4
7F69		Bottom	535,132	23	81	-4	14.6
7F70		Bottom	514,811	23	93	-4	14.0
7F71		Top	495,087	23	104	-4	13.5
7F72		Top	474,764	23	116	-4	12.9
7F73		Bottom	455,037	23	127	-4	12.4
7F74		Top	435,309	23	138	-4	11.9
7F75		Top	414,982	23	150	-4	11.3
7F76		Bottom	395,251	23	161	-4	10.8
7F77		Bottom	374,920	23	173	-4	10.2
7F78		Top	355,185	23	184	-4	9.7
7F79		Aug 4 ↓	Bottom	335,449	23	195	-5

Table 2. Far encounter photoreference data (continued).

Picture Number	Date	Shutter	Range, km.	Phase Angle, deg	Center of Disk		Resolution km/Pixel
					Longitude, deg	Latitude, deg	
Mariner 7 (continued)							
7F80	Aug 4 ↑ ↓ Aug 4	Bottom	315,112	23	207°W	-5	8.6
7F81		Top	295,370	23	218	-5	8.0
7F82		Bottom	275,625	22	230	-5	7.5
7F83		Bottom	255,279	22	241	-5	6.9
7F84		Top	235,527	22	252	-5	6.4
7F85		Top	215,173	22	264	-5	5.8
7F86		Bottom	195,412	22	275	-5	5.3
7F87		Top	175,645	22	286	-5	4.8
7F88		Top	155,273	22	298	-6	4.2
7F89		Top	150,478	22	300	-6	4.0
7F90		Bottom	145,084	22	304	-6	3.9
7F91		Bottom	140,288	22	306	-6	3.7
7F92		Top	134,892	22	309	-6	3.6
7F93		Top	130,095	22	312	-6	3.5

Mariner 7 - First Series

The first series of pictures, obtained by Mariner 7 (7F1-33), were taken from distances of 1.7 million km to 1.35 million km. These lower resolution pictures show the face of Mars from Solis Lacus (7F2) across the great Martian desert (Amazonis, Tharsis, Arcadia, Tempe), to the island Trivium Charontis (7F16), to Syrtis Major (7F28) and Sabaeus Sinus (7F33). Not much detail is revealed, but the same areas reappear later with much greater resolution. The edge of the South Polar Cap was noted to display a large irregularity.

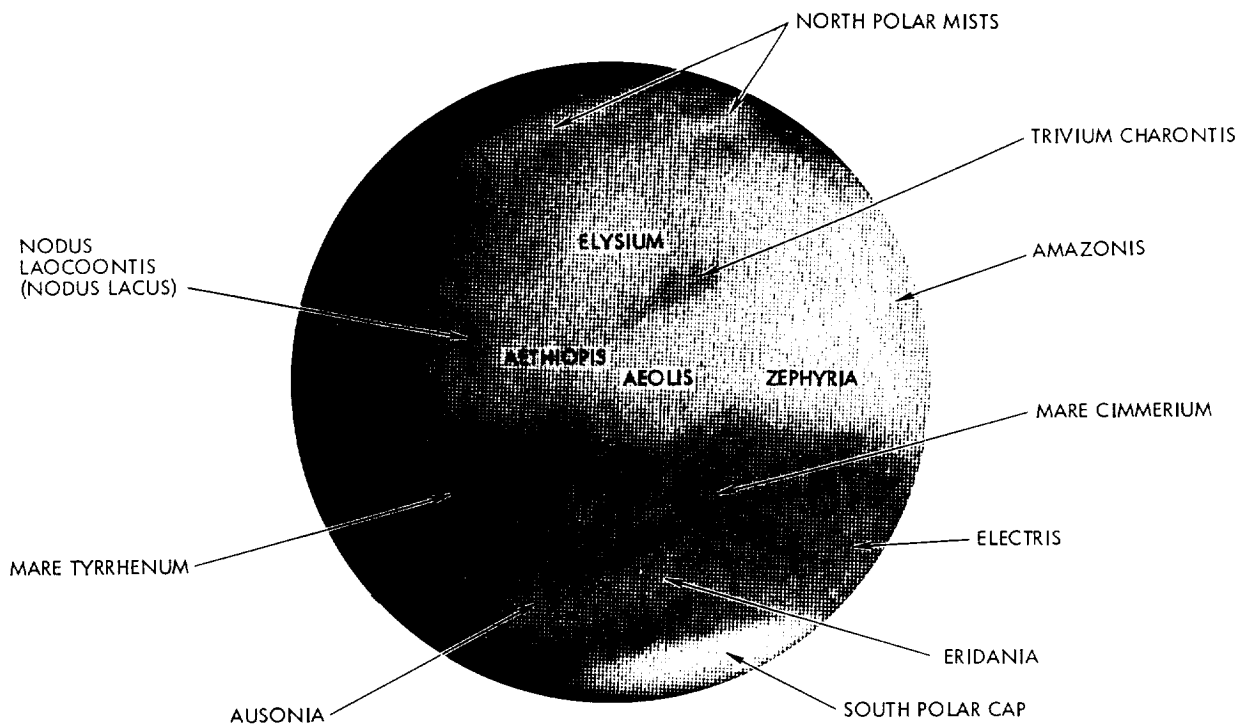


AUGUST 2, 1969

C.M. 121°

1.72 MKm

Fig. 5. Far Encounter Frame 7F2.



AUGUST 2, 1969

C.M.: 219°

1.55 Mkm

Fig. 6. Far Encounter Frame 7F16.

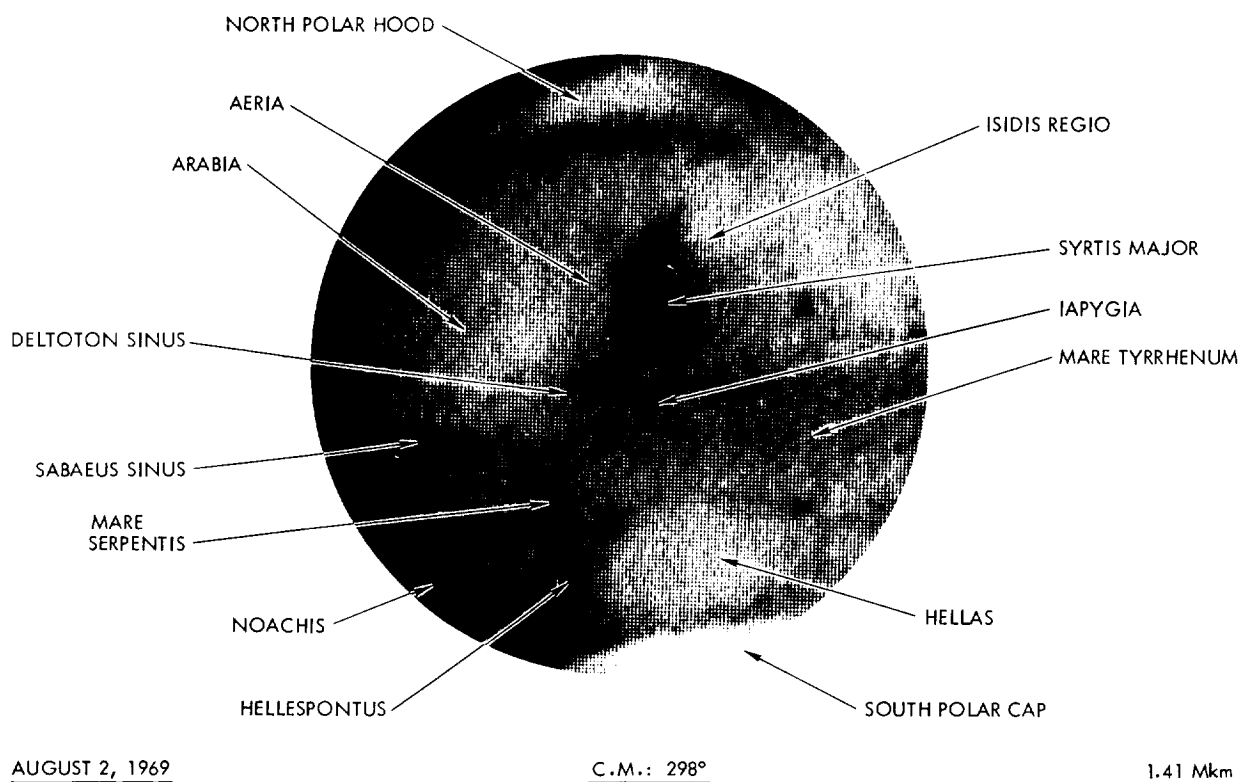


Fig. 7. Far Encounter Frame 7F28.

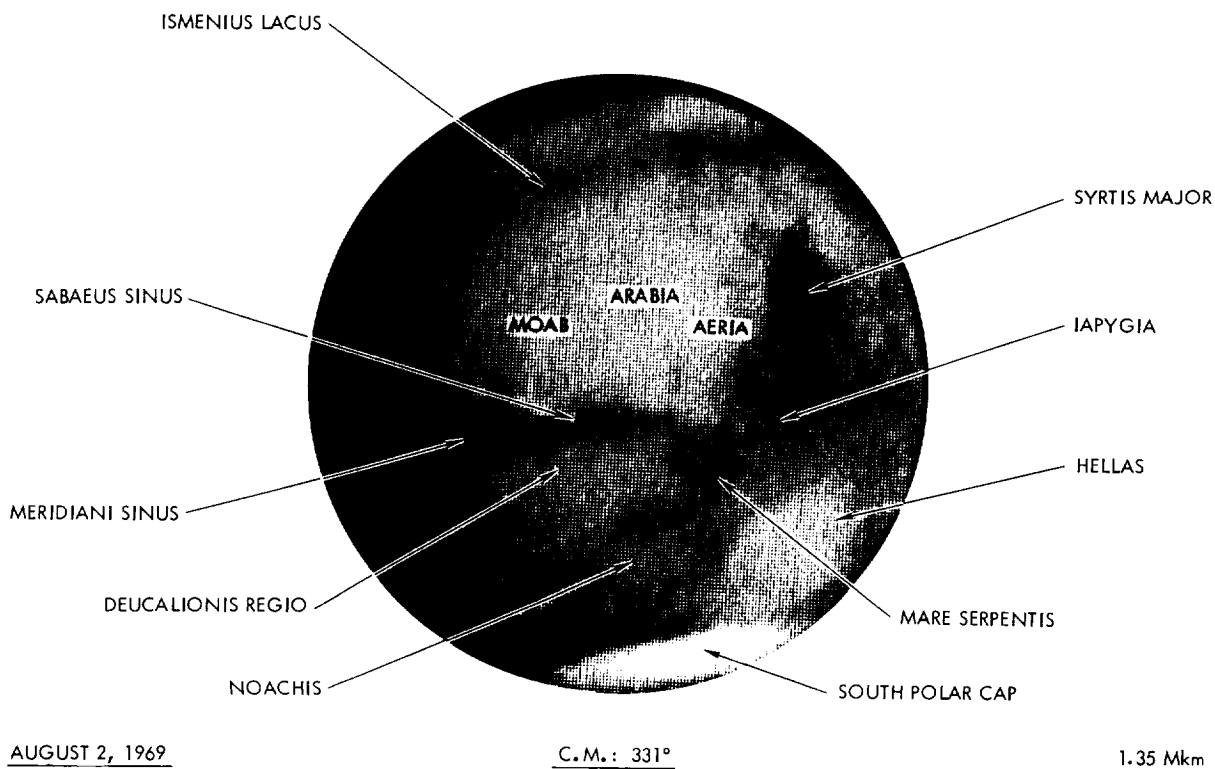
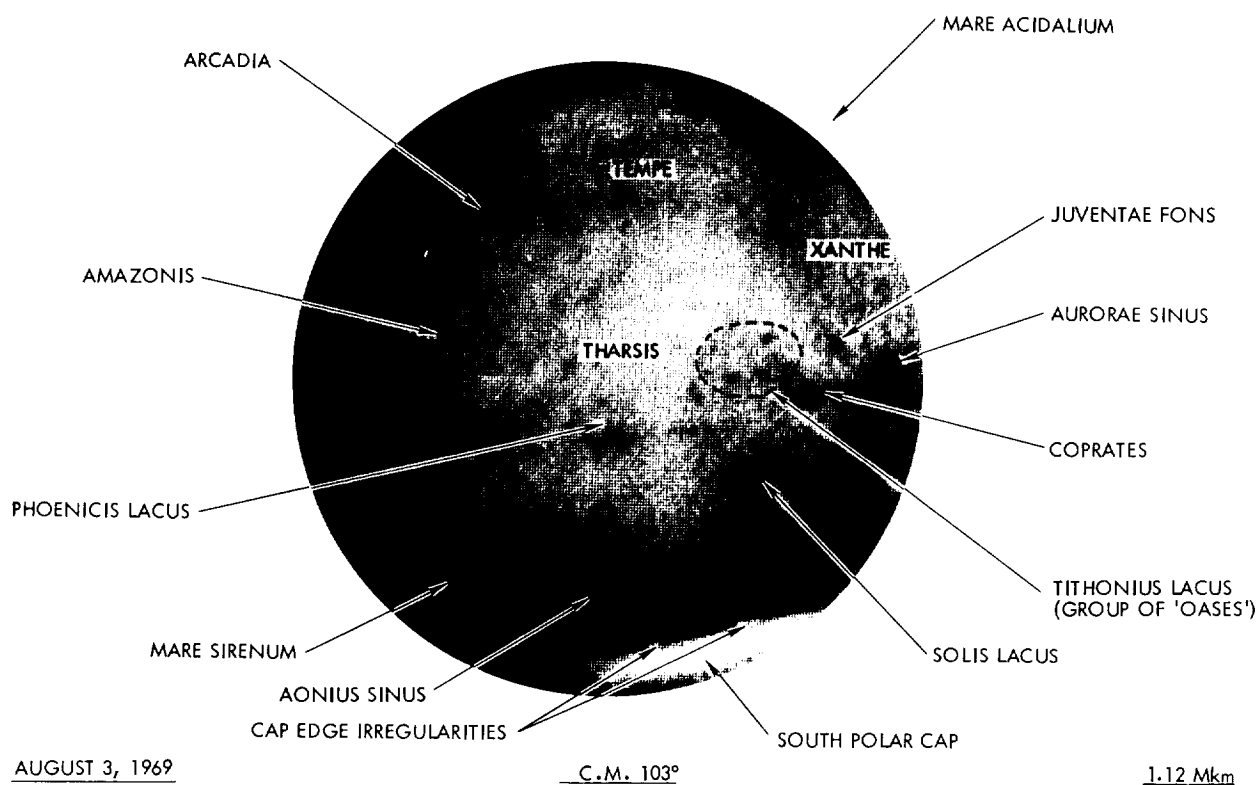


Fig. 8. Far Encounter Frame 7F33.

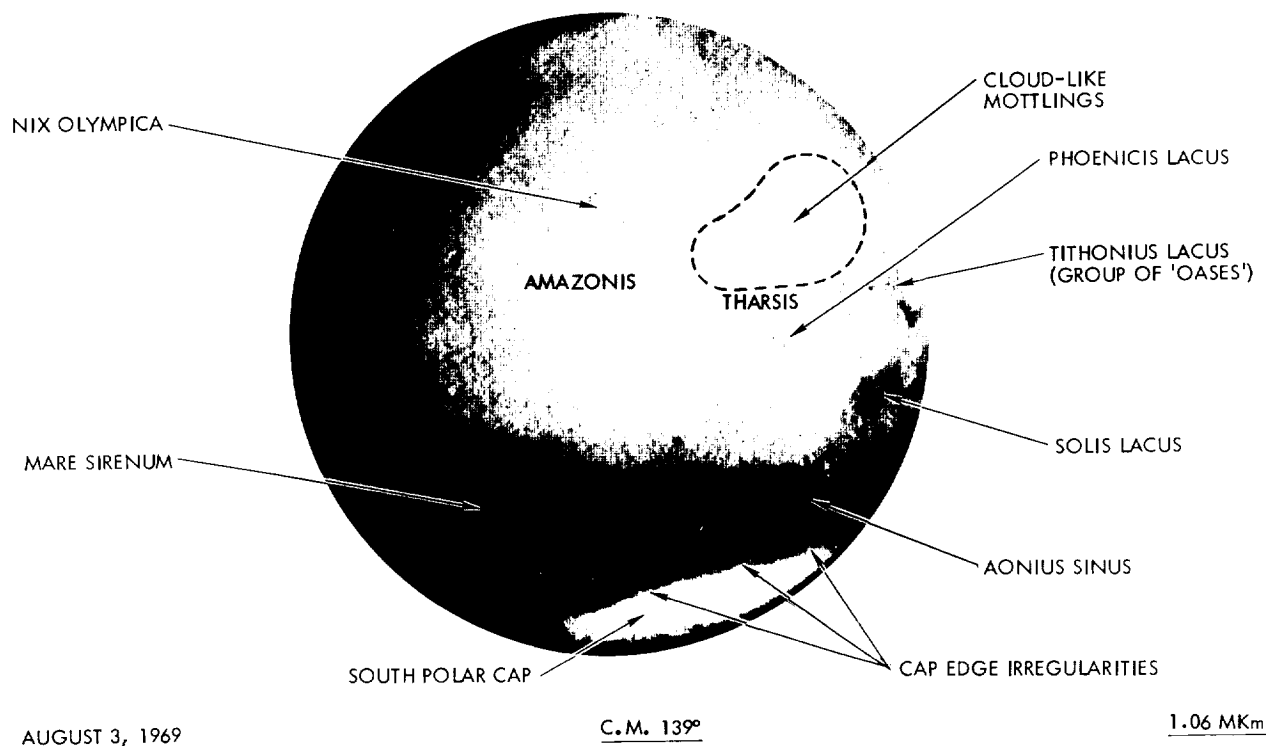
Mariner 6 — First Series and Mariner 7 — Second Series

The first series of pictures taken by Mariner 6 (6F1-33) and the second series obtained by Mariner 7 (7F35-67), both viewing the same area, start again at Solis Lacus and go all the way to Sabaeus Sinus, even to its termination into Meridiani Sinus. These pictures were taken from distances of 1.2 million km to approximately 700,000 km, at which distance the resolution attained becomes distinctly superior to that obtainable from Earth.



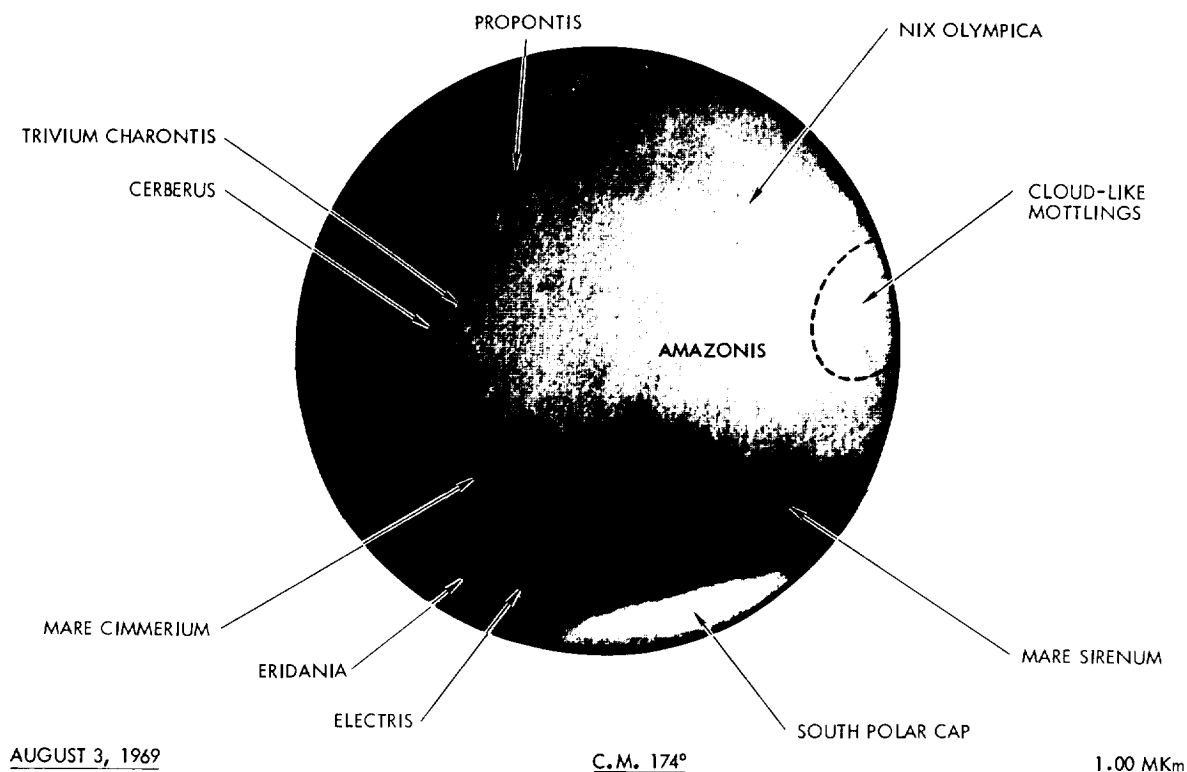
The complex area of Solis Lacus and Tharsis is seen with much fine detail in 7F40. The features known as Coprates Canal, Juventae Fons, Tithonius Lacus are clearly recognizable. The Phoenicis Lacus "oasis" to the west is less distinct. Notice in the south the large dark areas Mare Sirenum and Aonius Sinus hugging the brilliant South Polar Cap, and the two cap edge irregularities.

Fig. 9. Far Encounter Frame 7F40.



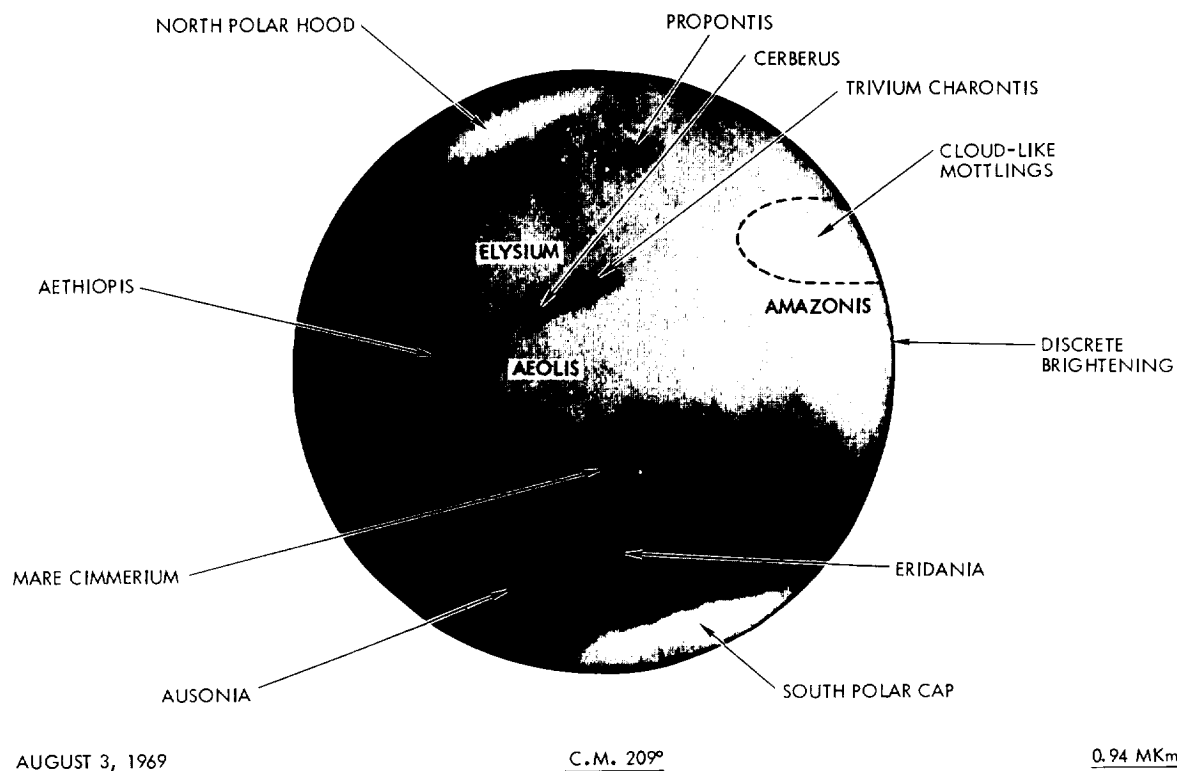
Northwest of the Solis Lacus area, the vast Amazonis-Tharsis desert appears in 7F44, where many paler mottlings are conspicuous. Notice a circular marking, which will be identified later as Nix Olympica.

Fig. 10. Far Encounter Frame 7F44.



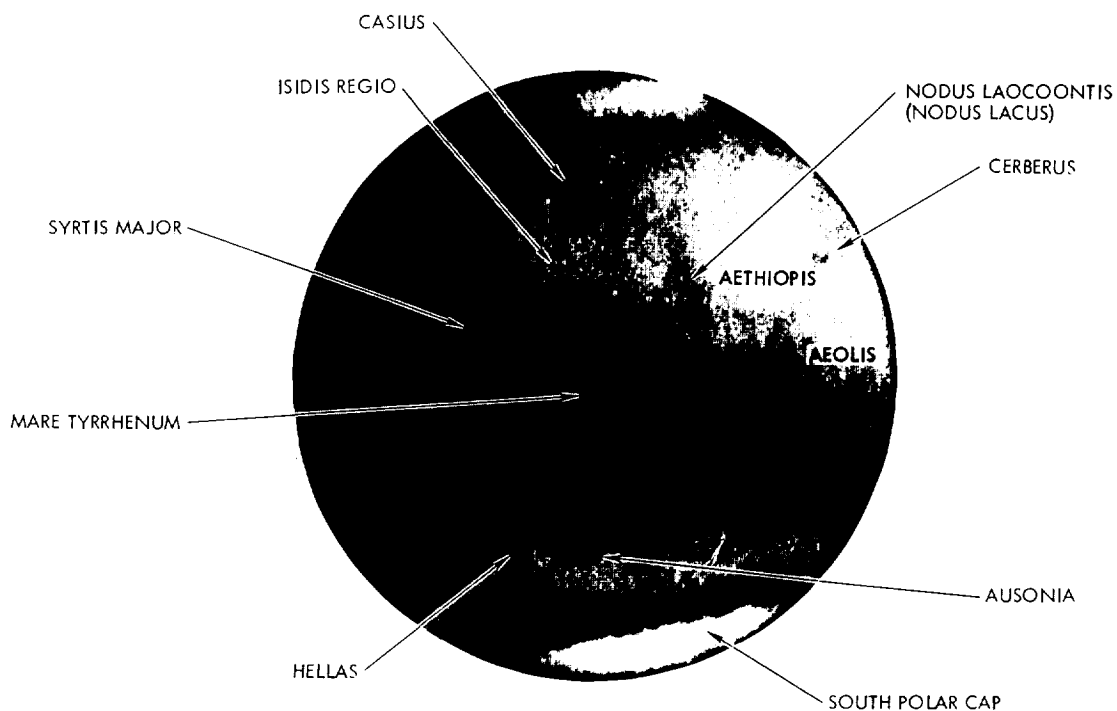
Trivium Charontis and Propontis, two large northern islands, appear in 7F48, while the large southern dark areas Mare Sirenum and Mare Cimmerium stretch across the disk uninterrupted, revealing an irregular border facing Amazonis. In the afternoon limb at the equator, a bright cloud-like mottling appears.

Fig. 11. Far Encounter Frame 7F48.



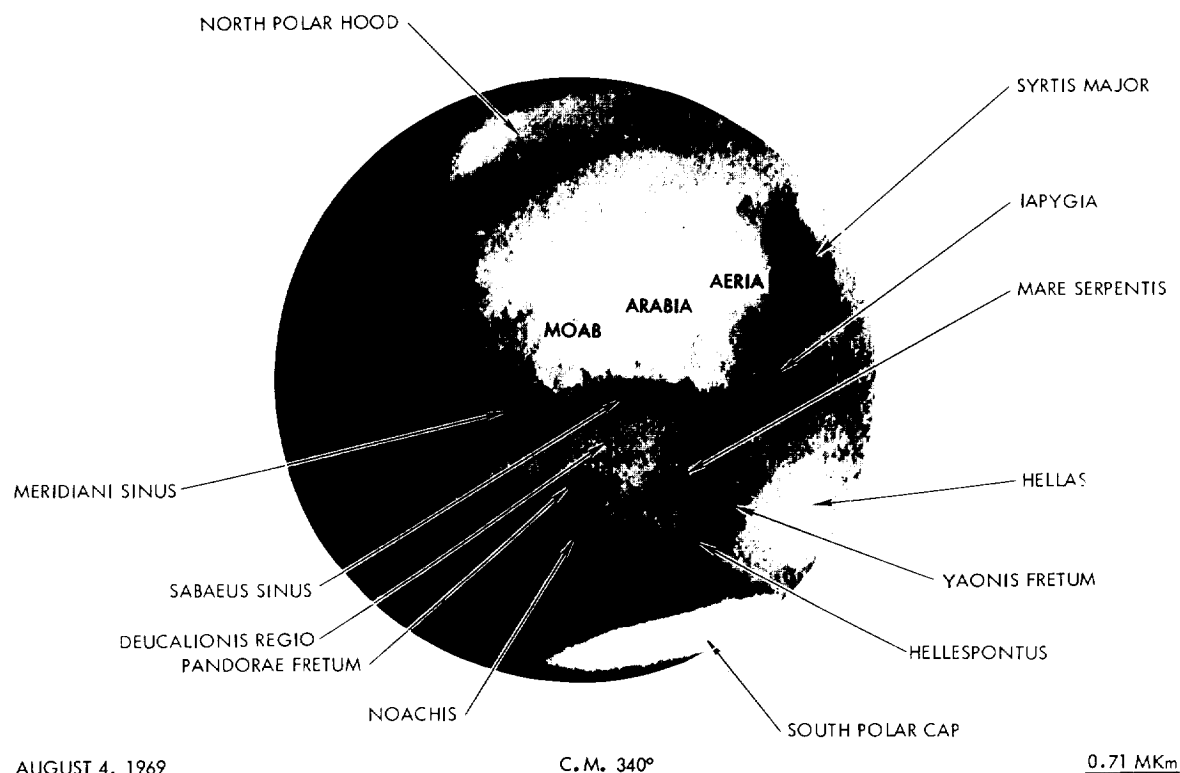
In 7F52, the north polar hood is quite conspicuous. It is also clear in the Mariner 6 pictures. Elysium appears bright above Trivium Charontis. Propontis stands out. Mare Cimmerium reveals a large protrusion, unmistakably the Cyclopa (Angustus Sinus) canal. The sharp outline of the South Cap has one large irregularity.

Fig. 12. Far Encounter Frame 7F52.

AUGUST 3, 1969C.M. 270°0.83 MKm

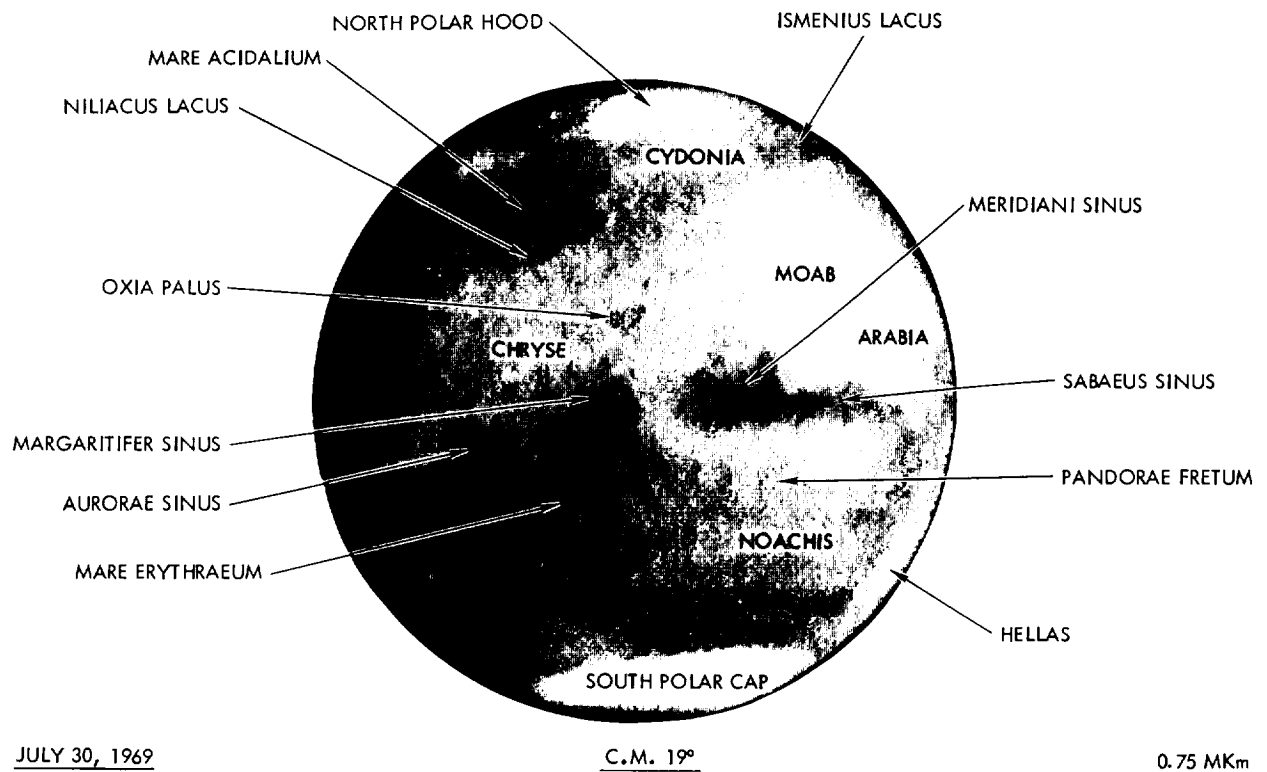
Syrtis Major reappears in the morning sun at the left in 7F59. In the center of the disk is the prominent dark Mare Tyrrhenum, with a large elongated island, often referred to as Nodus Laocoontis, off its irregular border. In the south, the bright patches of Ausonia merge into Hellas, which appears circular in other photographs.

Fig. 13. Far Encounter Frame 7F59.



7F67, taken at 700,000 km, shows (much better than Earth-based photographs) the "tree" formed by Hellespontus-Mare Serpentis as the trunk of the two boughs with Iapygia-Syrtis Major on the right and Sabaeus Sinus-Meridiani Sinus on the left. Below Iapygia, Hellas is quite conspicuous, and below Meridiani Sinus, Deucalionis Regio and Pandora Fretum are quite distinct. Above Sabaeus Sinus the three deserts Aeria, Arabia, and Moab are quite bright. None of the classical canals are visible.

Fig. 14. Far Encounter Frame 7F67.



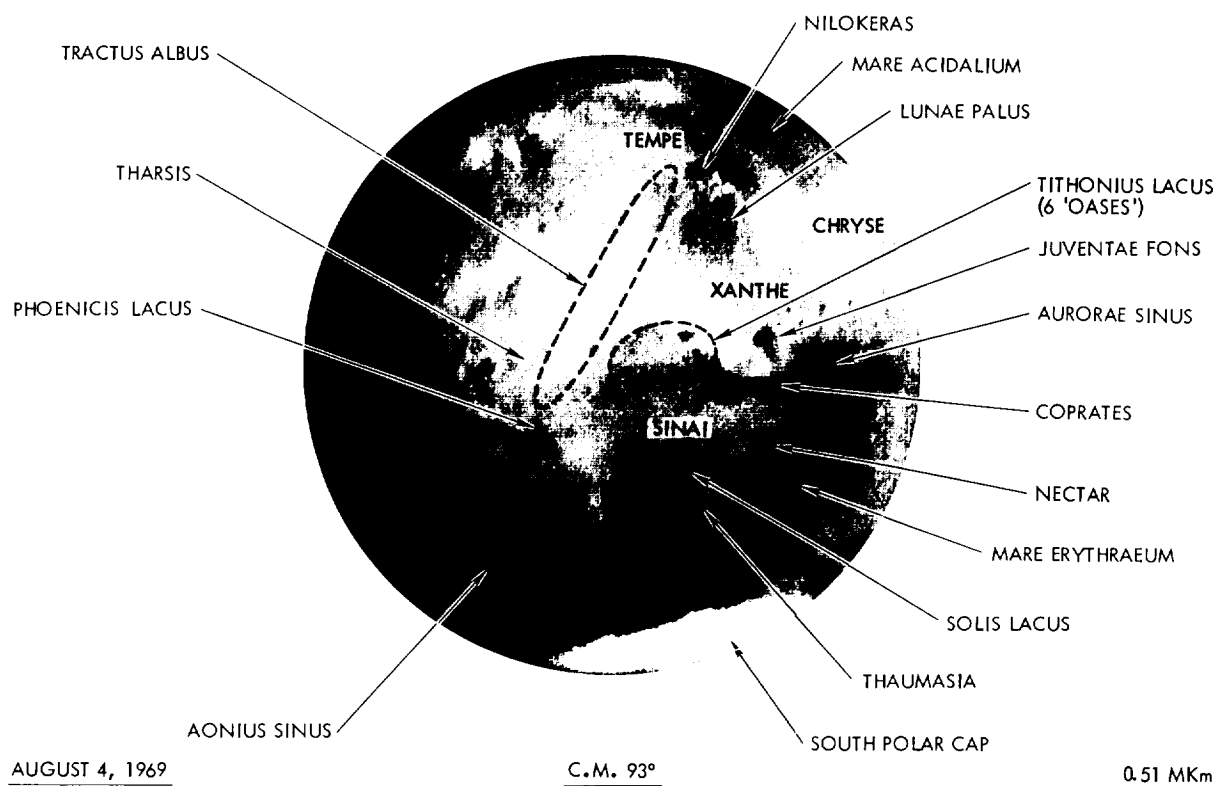
6F32 shows for the first time the face of Mars which was omitted by the gap between the first and second series of Mariner 7. In the center, bright Aram-Thymiamata separates the prominent Meridiani Sinus from Margaritifer Sinus along the equator. Below Pandora Fretum the desert Noachis appears diffuse, and below Margaritifer Sinus stretches Mare Erythraeum. The triangular Oxia Palus oasis is quite visible off the tip of Margaritifer Sinus, and in the north the large Mare Acidalium shows a sharp southern outline. Notice in all of the FE pictures the limb darkening of the South Polar Cap.

Fig. 15. Far Encounter Frame 6F32.

Mariner 7 - Third Series and Mariner 6 - Second Series

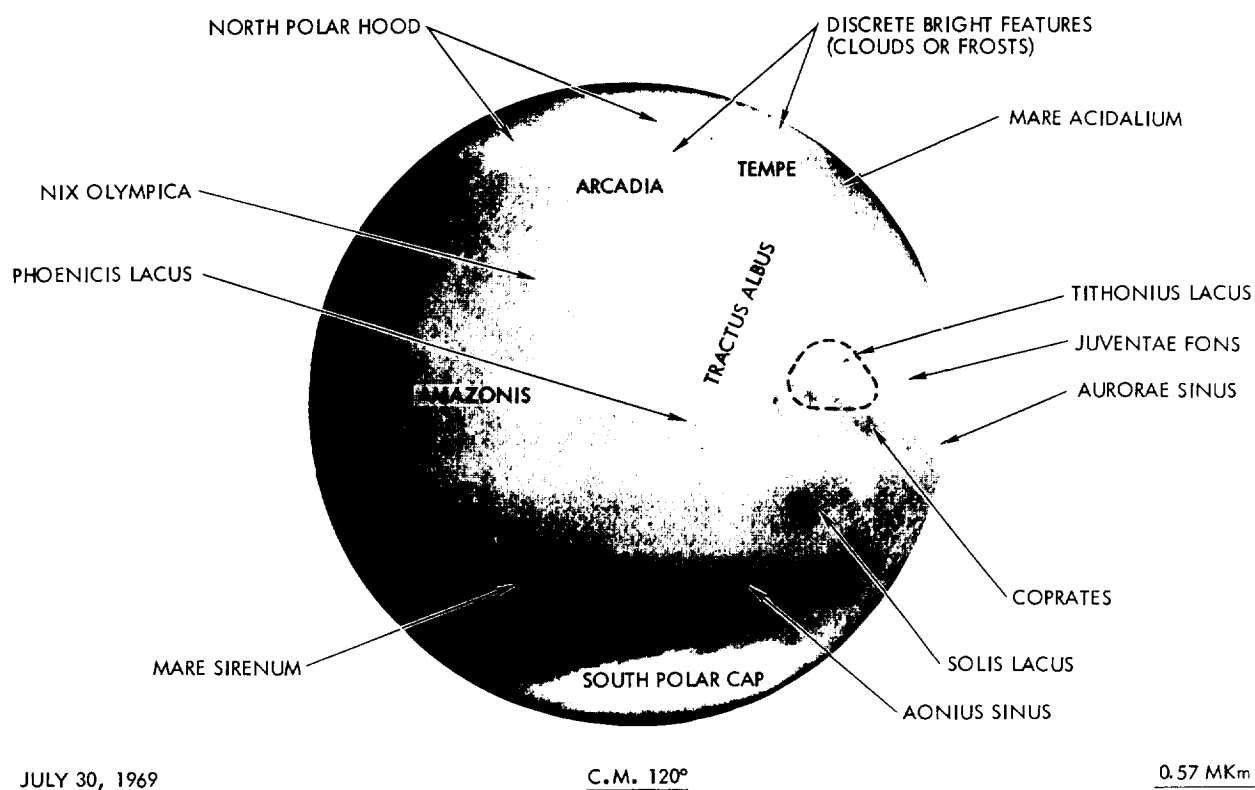
The final series of Mariner 7 Far Encounter photos, consisting of 25 pictures (7F69-93), was taken after an interruption of 6-1/2 hours and only the first eight are of the full disk. The distances were from 535,000 km (7F69) to 130,000 km (7F93). Mariner 6 took 16 pictures (6F34-49) in its second and last series. The distances were from 570,000 km (6F34) to 200,000 km (6F49), with only the first six pictures being of the full disk.

All these pictures are taken at distinctly better resolution than can be obtained from Earth.



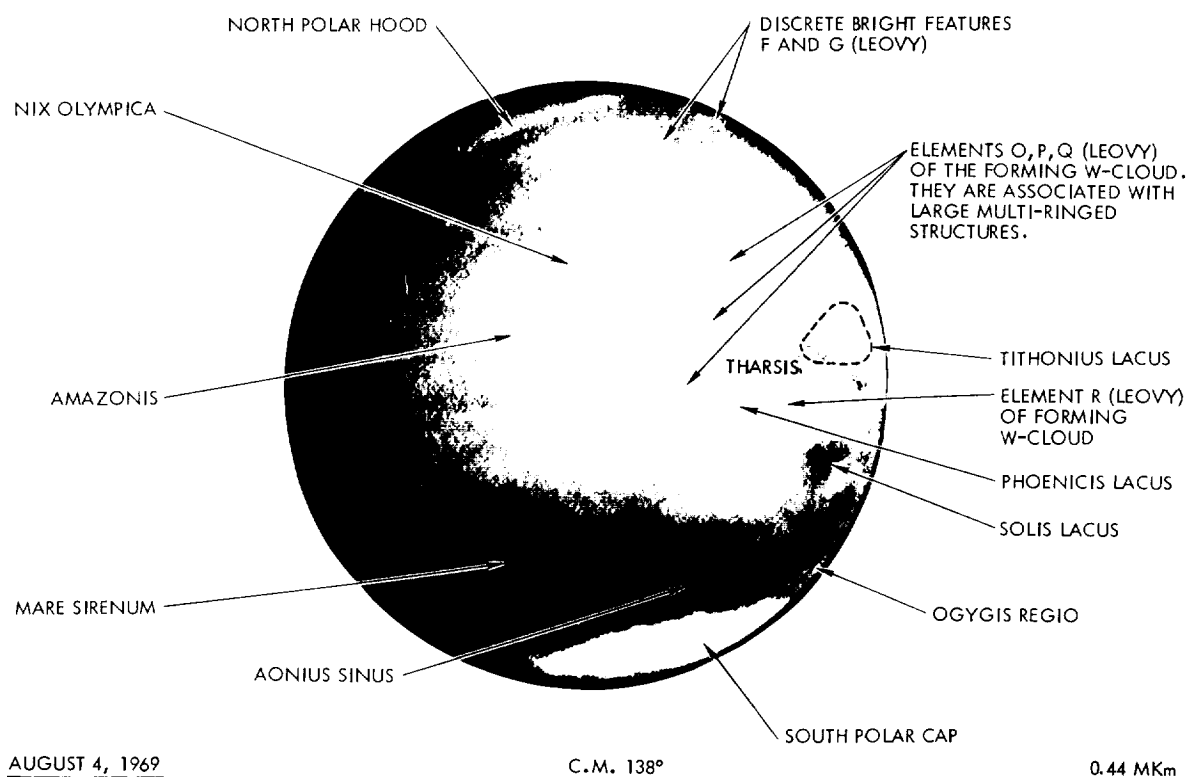
7F70 shows the Solis Lacus face of Mars for the third time, but now with a great wealth of detail heretofore unseen. The six or more components of the Tithonius Lacus multiple oasis are entirely resolved. Phoenicis Lacus is well resolved as the right 'twin' arrowhead. Juventae Fons remains a single large black dot, while Coprates (Agathodaemon) is seen to be a continuous unusually large elongated peninsula rather than a canal. Solis Lacus is linked to Mare Erythraeum by a twisted channel swollen into a large knot recognized as Nectar. It is well known that both Solis Lacus and Nectar have varied much in size and shape in the past. In the Tharsis area a number of circular bright streaks are visible around dark centers. In the north the southwestern double promontory, Nilokeras, of Mare Acidalium is very conspicuous. In the desert Chryse just off Aurorae Sinus a number of smaller black dots and/or streaks are noticeable. A cleft is visible in the edge of the South Polar Cap.

Fig. 16. Far Encounter Frame 7F70.



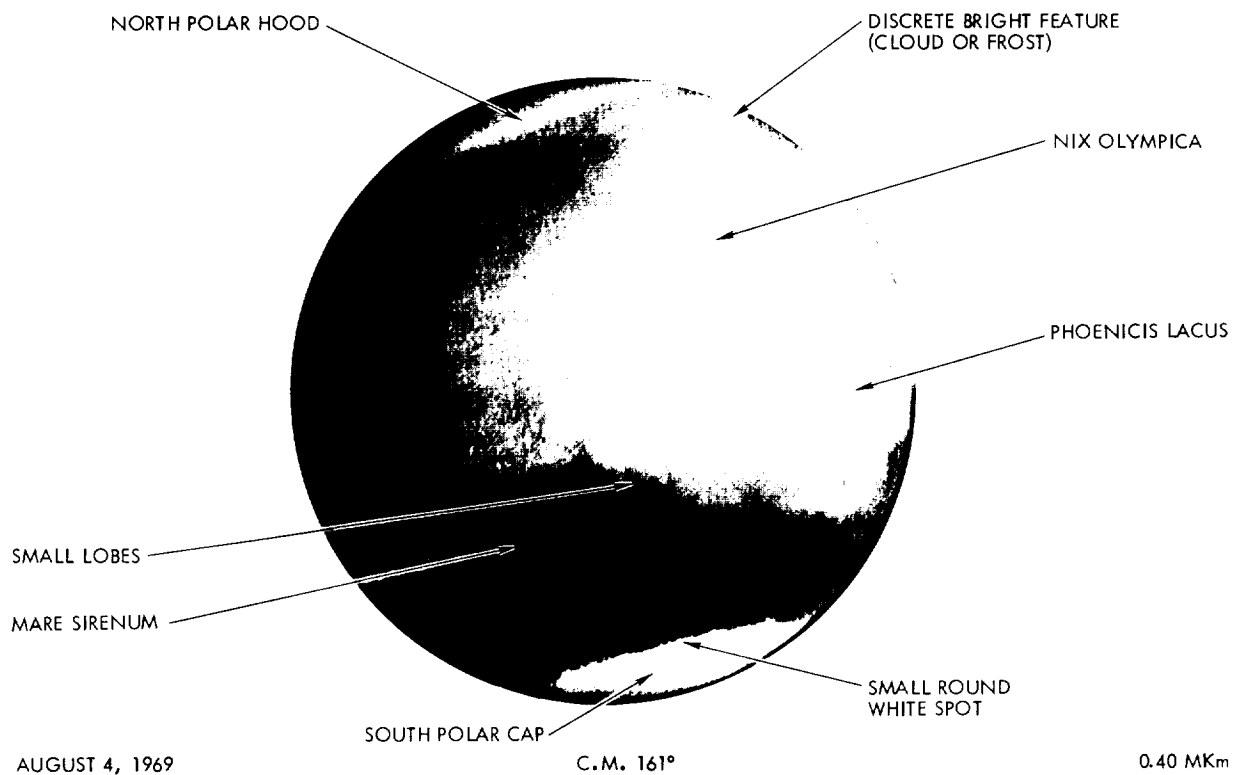
6F34 has much less contrast but shows the north polar hood as rather extensive and irregular, with at least two brighter cloud-like tongues, which will rotate nearly unchanged with the planet.

Fig. 17. Far Encounter Frame 6F34.



7F74 reveals annular Nix Olympica as a white ring with a white central dot. Its appearance is suggestive of a very large crater with frost-covered rims and a central peak. Other large multiringed structures are present to the southeast of Nix Olympica. With these are associated diffuse cloud masses which are enlarging and brightening during the afternoon to form a W-pattern. Cloud elements O, P, Q, R, as labelled by Leovy are indicated here.

Fig. 18. Far Encounter Frame 7F74.



7F76 shows again the region of Nix Olympica. The Amazonis-Tharsis desert, southeast and west of it, is strangely streaked, ringed and dotted into a complex of subtle pale markings. The shores of Mare Sirenum are sharp and irregular with protrusions in the form of lobes and even a finger. It is interesting to mention that the Mariner 4 track was located across Mare Sirenum as indicated in Fig. 20.

Fig. 19. Far Encounter Frame 7F76.

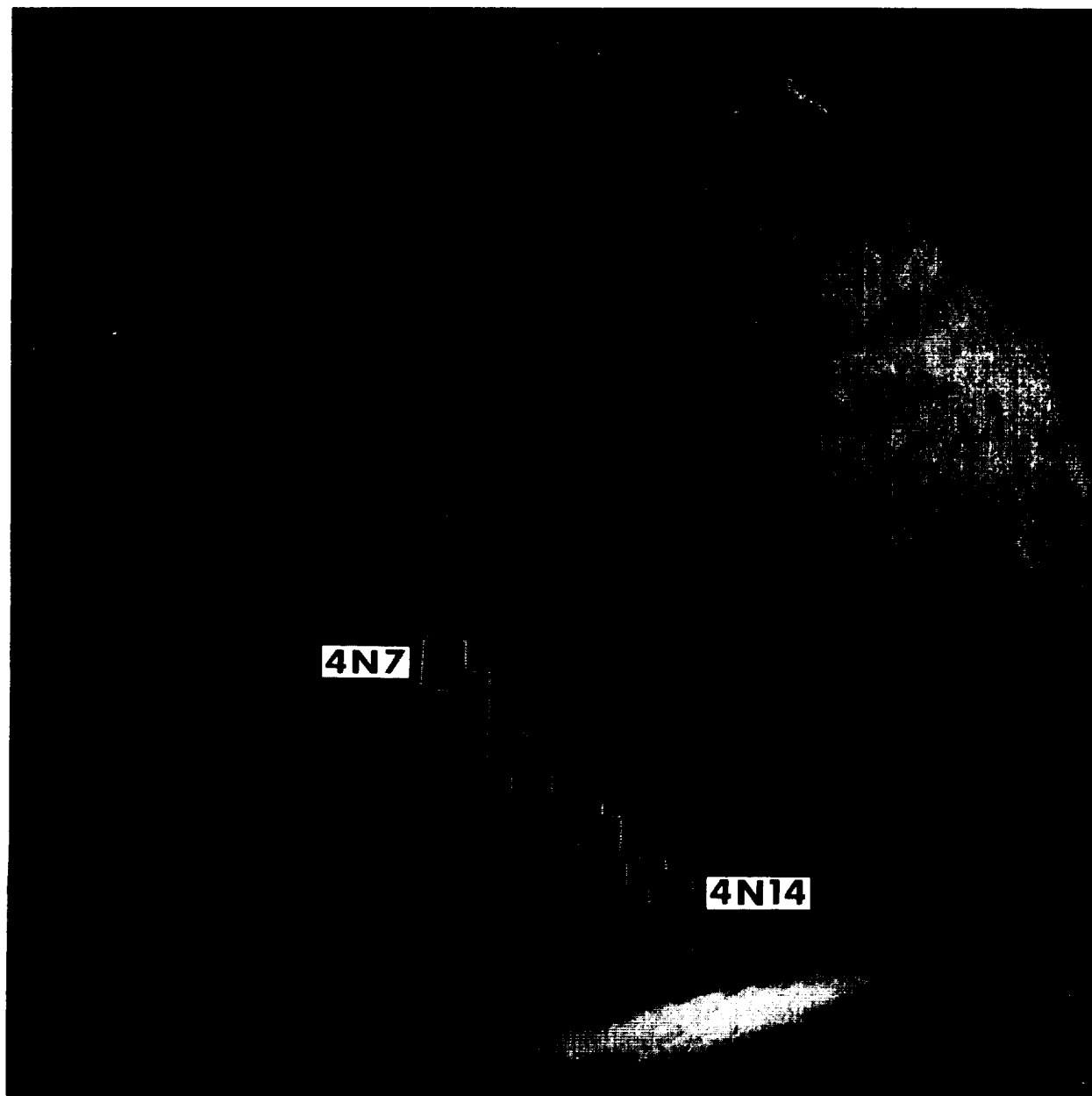
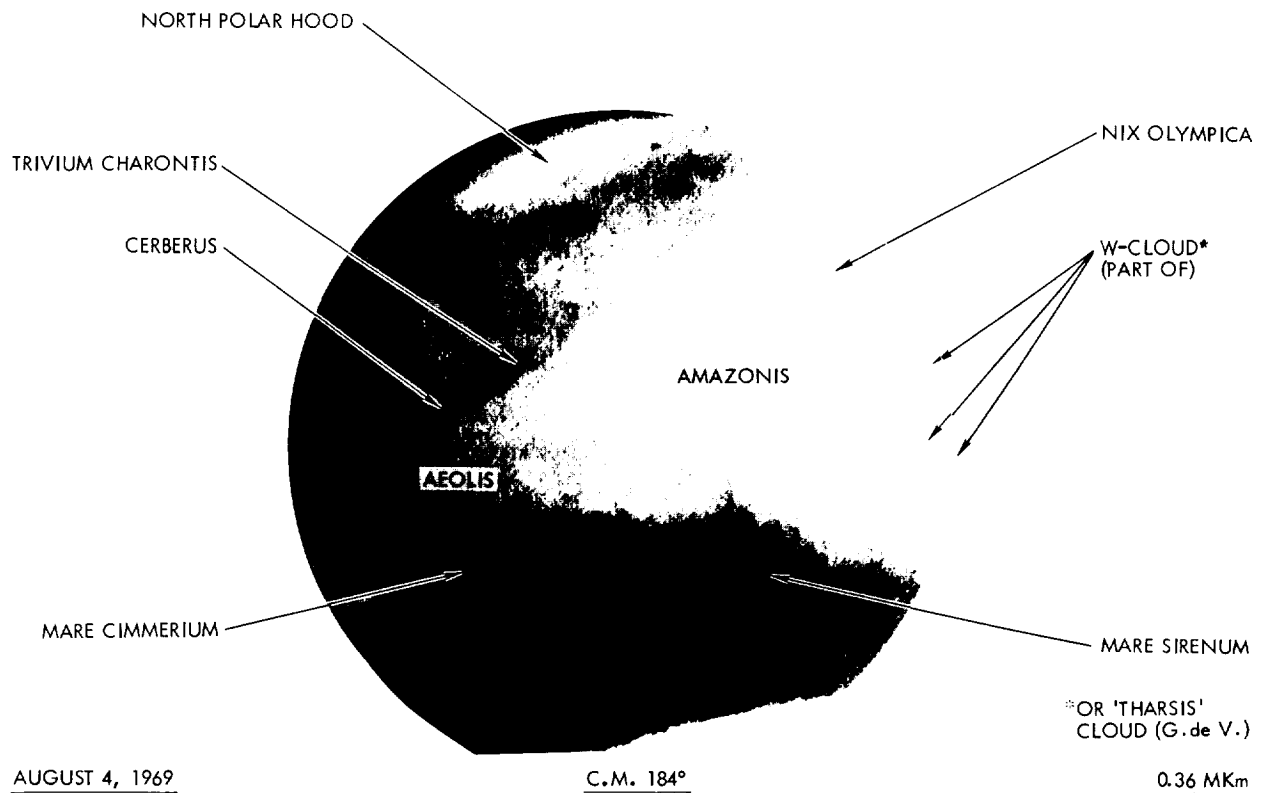
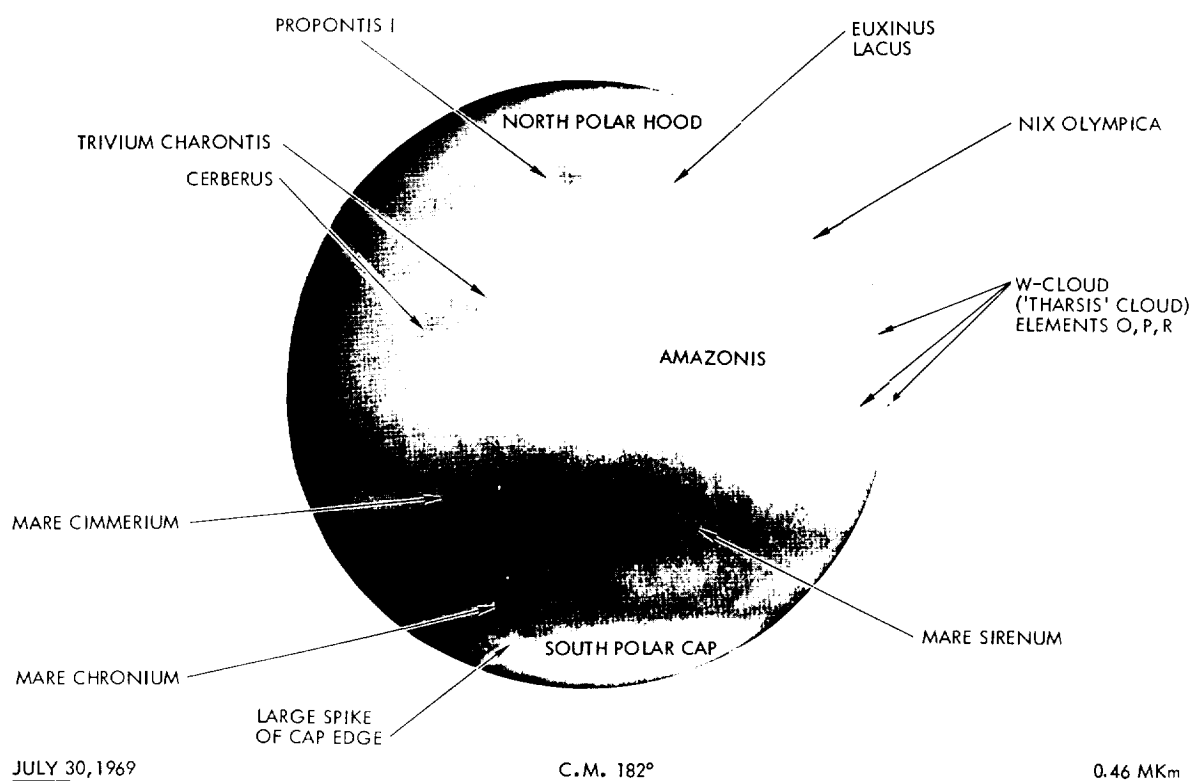


Fig. 20. Far Encounter Frame 7F76 modified to show the positions of Mariner 4 pictures 4N7 through 4N14.



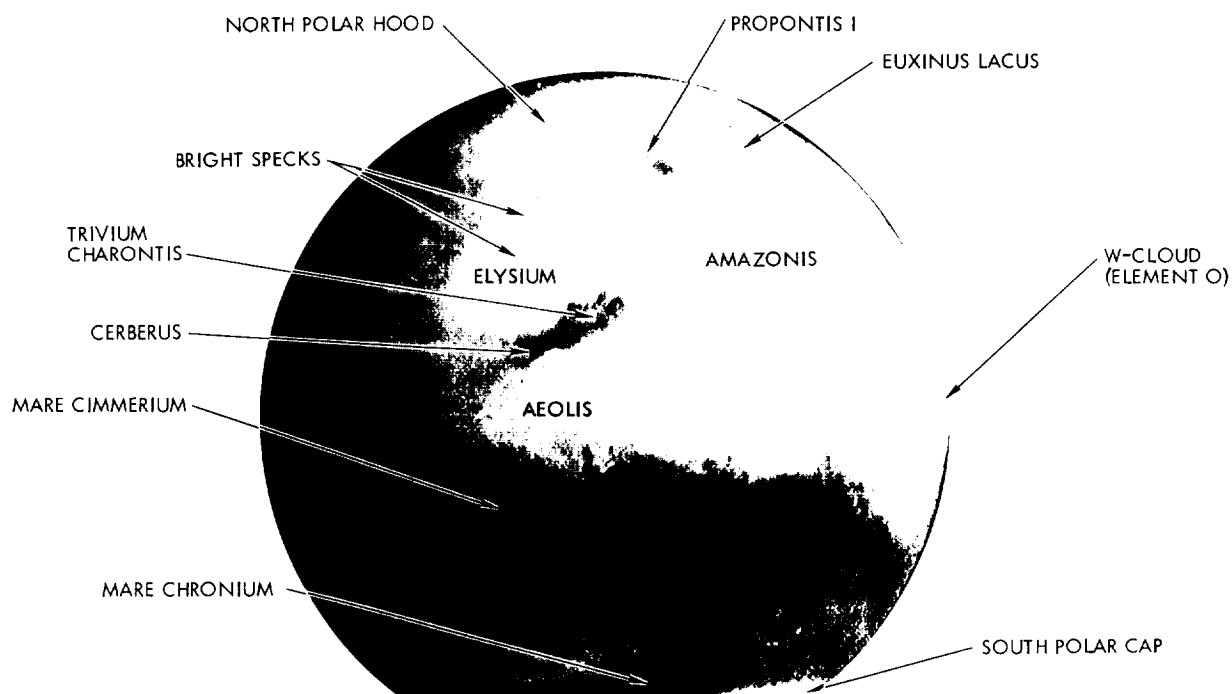
7F78 shows on the eastern limb the seasonal "W cloud" over Tharsis which is a well-known afternoon recurrence at that time of the year. Whether the phenomenon is actually a cloud or ground frost is not yet known. The development of this bright feature is seen from 7F77 to 7F79, or 6F38 and 6F39.

Fig. 21. Far Encounter Frame 7F78.



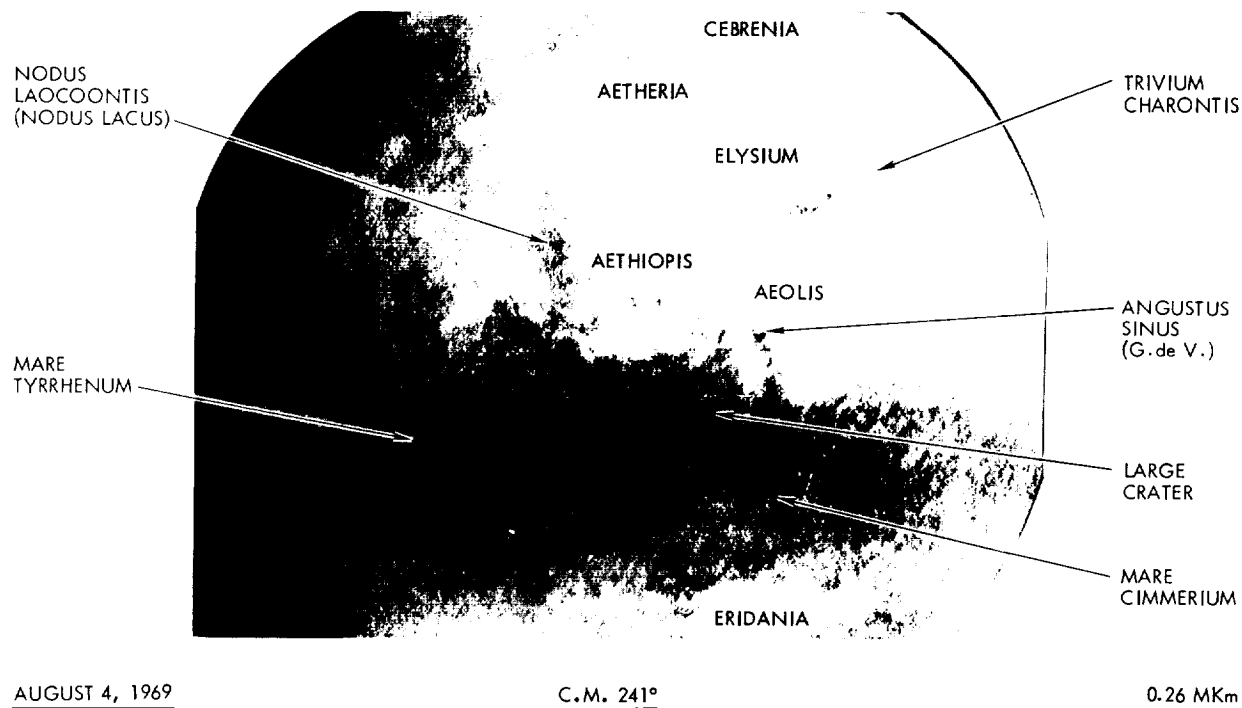
6F38 also shows the development of a portion of the W-cloud, but on another late afternoon five days earlier. The North Polar haze is quite extensive as in preceding frames. Below it the two elongated large dark forms entering at the western end of Amazonis are Propontis and Trivium Charontis-Cerberus. The South Polar Cap exhibits a fairly prominent spike on its morning side; this makes a sizable encroachment into Mare Chronium bordering it, below Mare Cimmerium.

Fig. 22. Far Encounter Frame 6F38.

AUGUST 4, 1969C.M. 207°0.32 MKm

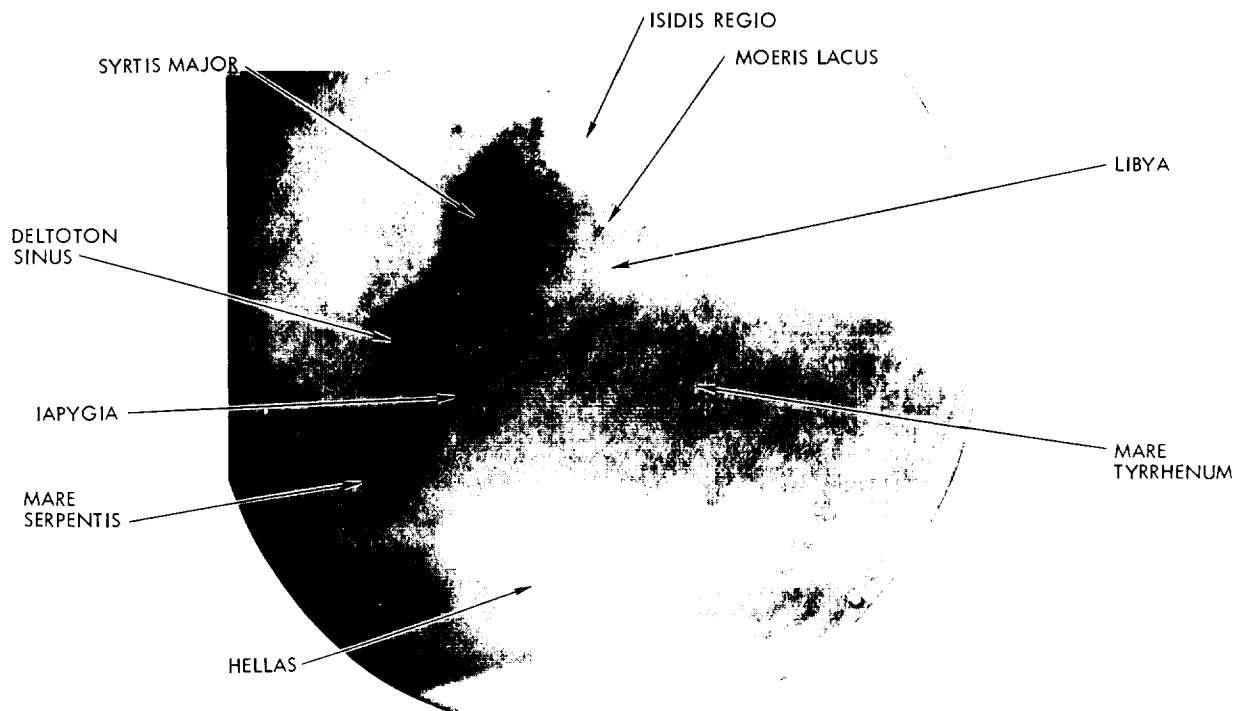
7F80, taken at 315,000 km, shows the interesting fish-like structure of the Trivium Charontis-Cerberus complex, a famous variable feature. Bright Elysium above appears strikingly pentagonal and here speckled with two brighter spots also seen in the Mariner 6 pictures. Prominent Mare Cimmerium displays a multitude of finger-like extensions into Aeolis.

Fig. 23. Far Encounter Frame 7F80.



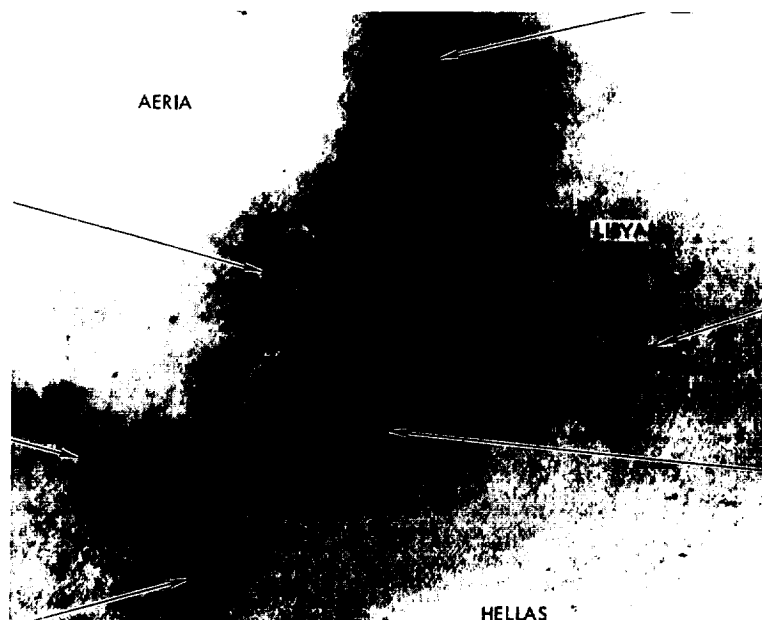
7F83 shows more of the ragged shores of Mare Cimmerium; the large finger Cyclopia (Angustus Sinus) seems to be a chain of craters. The interior of the large Mare Cimmerium appears riddled with similar circular features. The brightness of Elysium is decreasing with the afternoon hours. The surrounding deserts Aeolis, Aethiopia, and Aetheria are in view. On the boundary of Aethiopia the large island known as Nodus Laocoontis has diffuse form.

Fig. 24. Far Encounter Frame 7F83.

JULY 30, 1969C.M. 282°0.28 MKm

6F46 exhibits the entire Syrtis Major-Hellas region. Note the circularity and northern brightness of Hellas, probably due to haze. The feature known as Zea Lacus is not visible in any of the FE pictures.

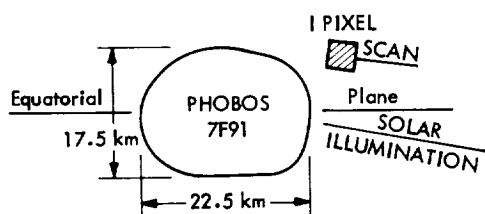
Fig. 25. Far Encounter Frame 6F46.



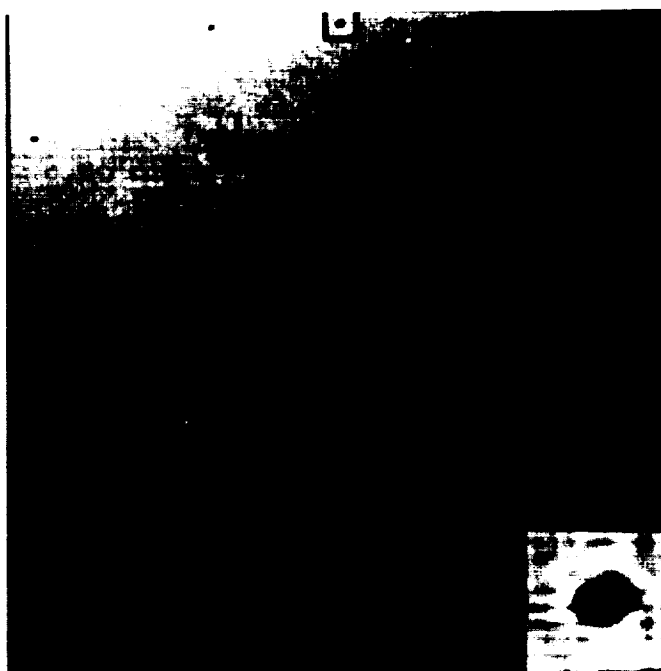
7F91, taken at 140,000 km from Mars, gives a closeup view of the area linking Syrtis Major to northern Hellas and Sabaeus Sinus. In Iapygia, a very large crater is seen, while numerous smaller craters are unmistakably recognizable in the Deltoton Sinus promontory and across Iapygia. Craters are even visible in the neighboring light areas Aeria on the left and Libya on the right, but they are more subdued in contrast.

Fig. 26. Far Encounter Frame 7F91.

MARINER 7 PHOTOGRAPHED
MARS' MOON PHOBOS
OVER THE DESERT AERIA
ON 4 AUG. 1969 23:35:34
INSET IS X4 MAGNIFICATION

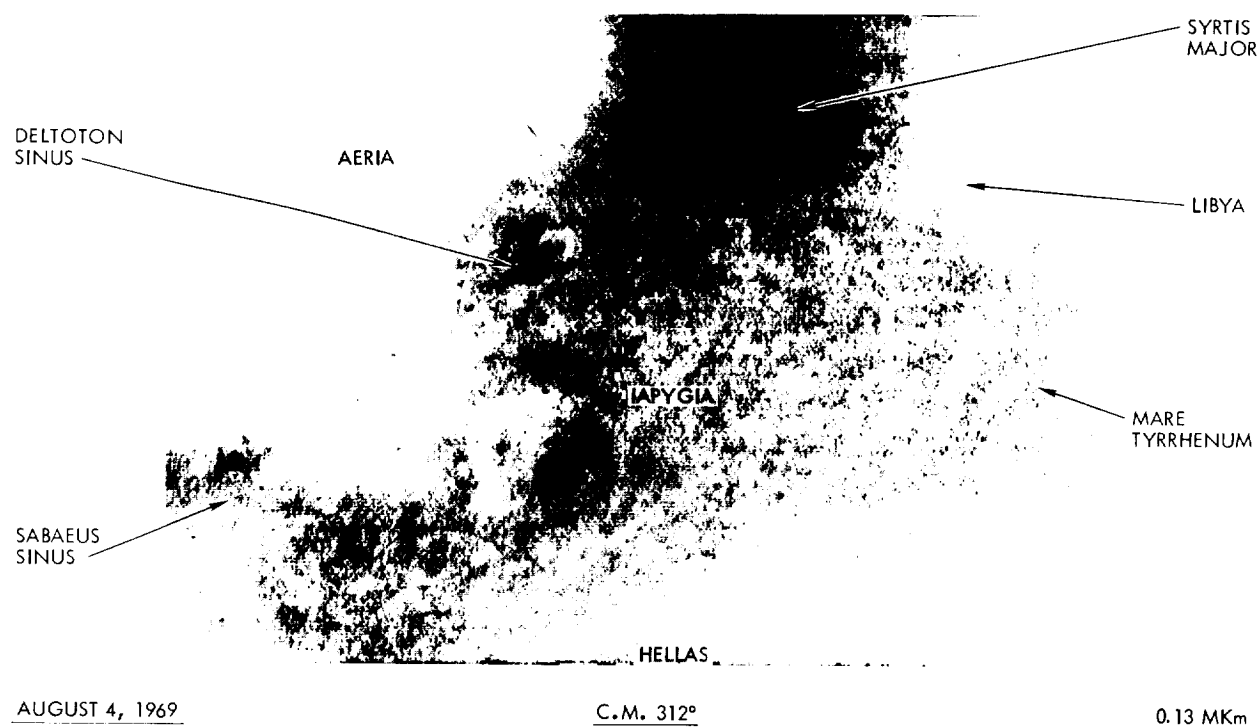


Limb profile of Phobos in frame 7F91. The size of a single television picture element (pixel) and vidicon scanning direction is indicated. The orbital plane of Phobos (not shown) lies nearly in the Martian equatorial plane. Geometric corrections and coherent noise removal have changed the shape from that seen in the raw version (Smith, 1970).



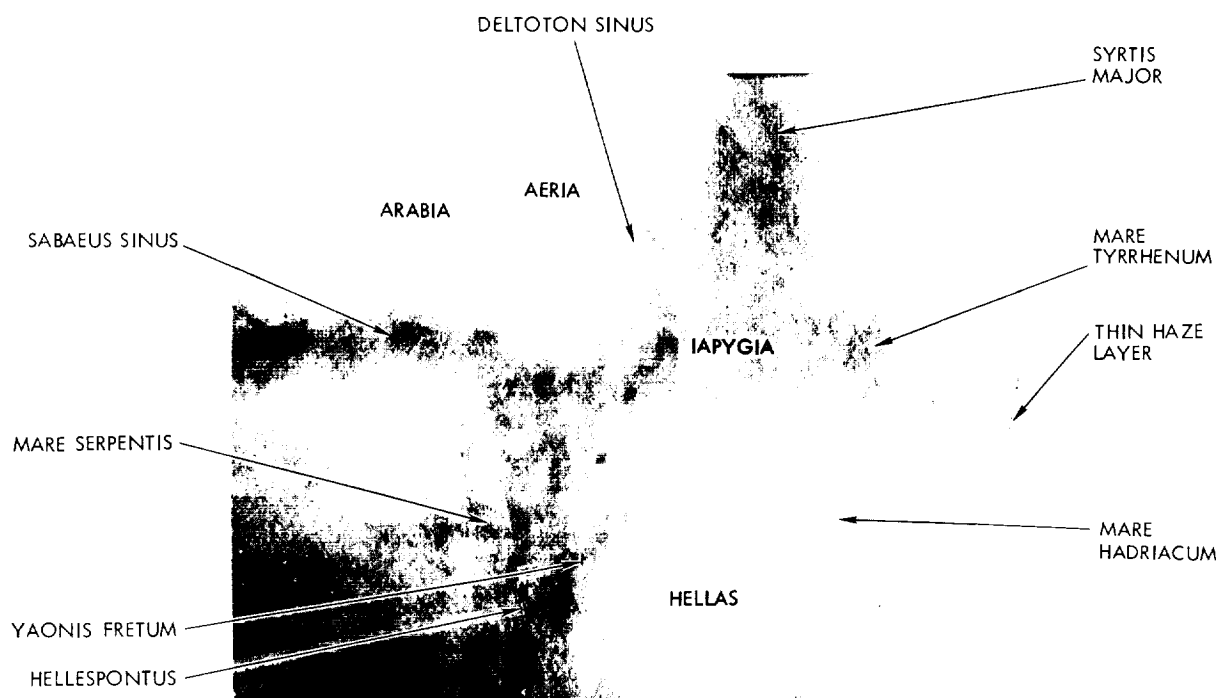
An enlarged portion of 7F91 (16 times) showed the image of Phobos as an oval-shaped, dark object (see upper portion of picture). Only four other FE frames have positively shown Phobos.

Fig. 27. Far Encounter Frame 7F91 (magnified portion showing Phobos).



7F93, taken at 130,000 km, is the last and closest FE frame and is centered on Iapygia, showing clearly the large crater over 300 km across, mentioned earlier, as well as other craters surrounding it.

Fig. 28. Far Encounter Frame 7F93.



JULY 30, 1969

C.M. 322°

0.21 MKm

6F49, taken at 200,000 km from Mars, is the last of the Mariner 6 FE pictures. It shows in large scale Sabaeus Sinus, Mare Serpentis, and Iapygia with its enormous crater, and portions of the deserts Noachis and Hellas where thin haze layers seem to be present. Note the irregular northern edge of Sabaeus Sinus. Mare Tyrrhenum and Mare Hadriacum on the right limb are rather diffuse, perhaps because of the same veil of haze.

Fig. 29. Far Encounter Frame 6F49.

3.6.2 NEAR ENCOUNTER

The near-encounter (NE) period, lasting about 20 minutes, was centered on closest approach of the planet and provided 59 pictures, some as close as 3500 km, with a resolution attaining 0.3 km. The photographic coverage by the two spacecraft encompassed over 10% of the Martian surface, dependent on slant range (and perhaps 20% if limbs are included), mostly of the Southern Hemisphere. Mariner 6 took 26 NE pictures covering an equatorial swath (from 0 to 25°S latitude), and five days later Mariner 7 took 33 NE pictures covering both a mid-latitude and polar swath in the Southern Hemisphere. Two resolutions were used alternatively: the low resolution pictures (3 km at best) were taken with the wide-angle camera "A," and the high resolution pictures (0.3 km at best) with the narrow-angle camera "B." The approximate picture locations are illustrated on painted globes of Mars, one for each spacecraft, as seen in Figs. 30 and 31.

The following pages present a selection of the most significant NE pictures, each illustrating a particular aspect of the Martian surface or atmosphere. The classification is somewhat arbitrary. The caption comments, however, place the emphasis on the main aspect as indicated by the six groupings which are as follows:

- 1) Cratered Terrain
- 2) Chaotic Terrain
- 3) Featureless Terrain
- 4) Atmospheric Haze (Limb Pictures)
- 5) Dark and Light Areas (Meridiani Sinus Complex)
- 6) South Polar Cap

Each of the above groupings is introduced by at least one mosaic providing a panoramic spacecraft view of the regions encompassed. Odd-numbered pictures were taken by camera A and even-numbered pictures by camera B. The Near Encounter Photoreference Data, Table 3, provides specific data for each of the NE pictures taken.

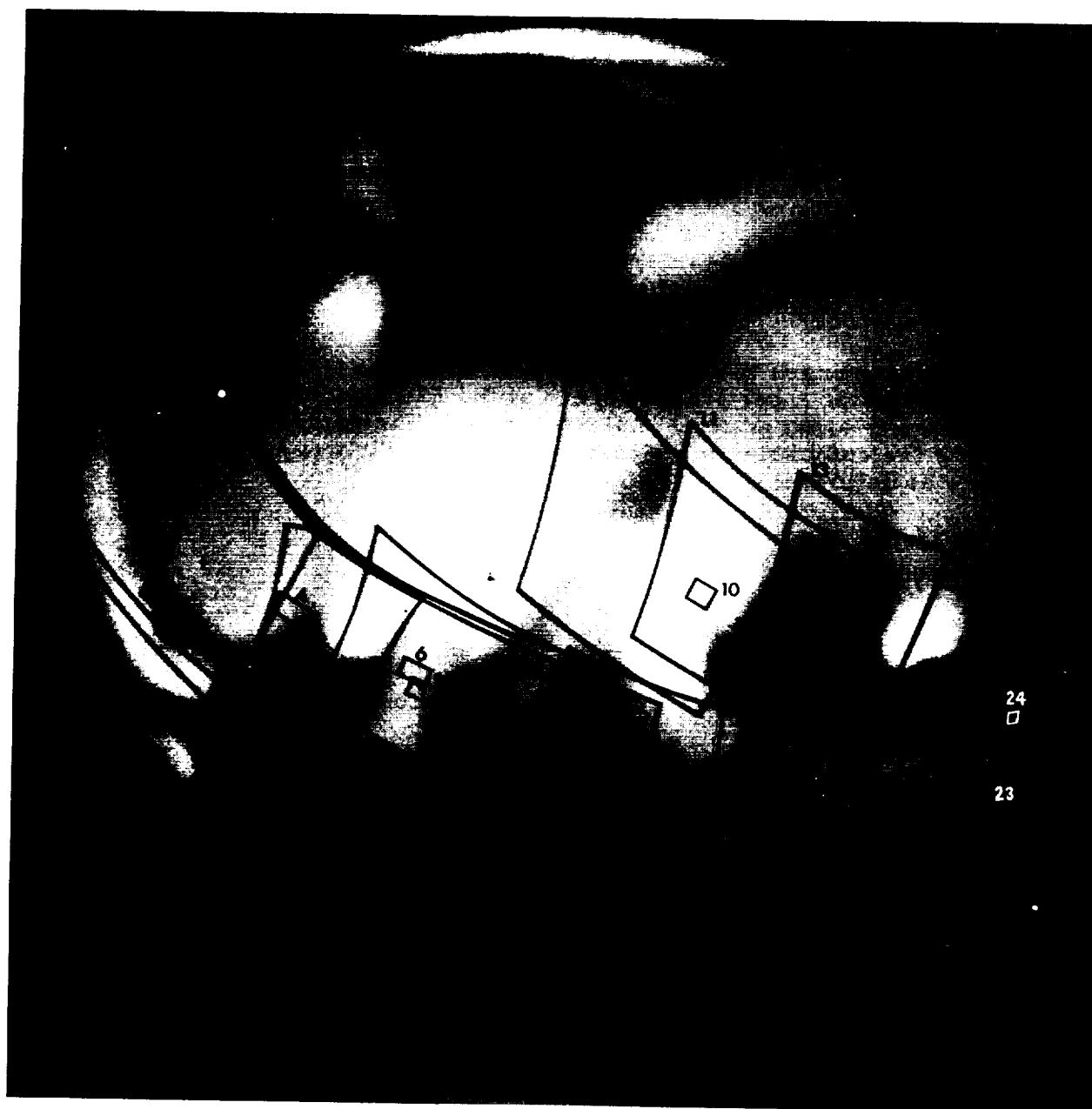


Fig. 30. Mariner 6 picture locations on a painted globe of Mars.

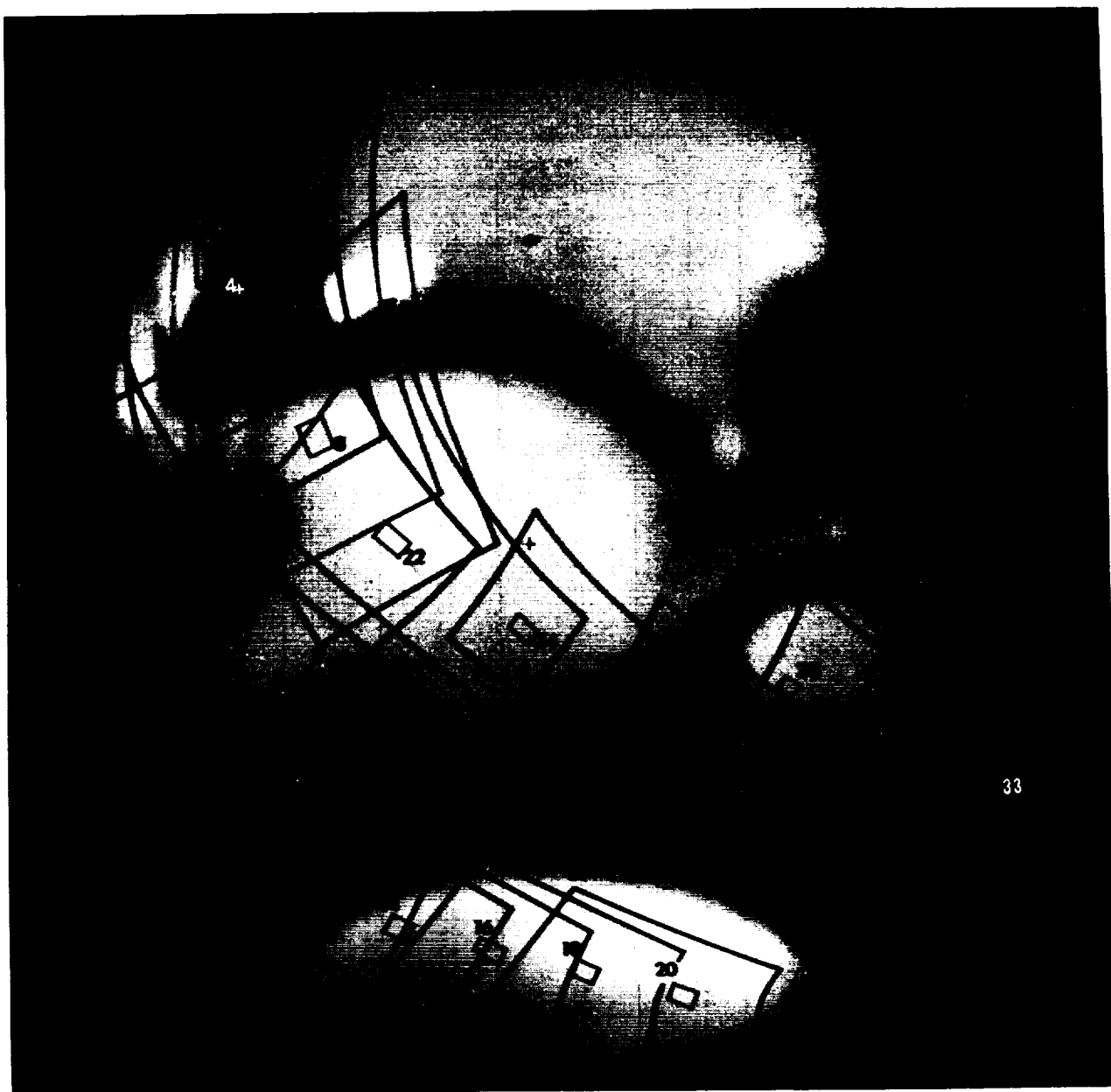


Fig. 31. Mariner 7 picture locations on a painted globe of Mars.

Table 3. Near encounter photoreference data.

At Center of Picture									
Picture Number	Shutter or Filter	Slant Range, km	Phase Angle, deg	Solar Elevation Angle, deg	Viewing Angle, deg	Longitude, deg W	Latitude, deg	Picture Dimen. on Surface, km	
								Horiz	Vert
Mariner 6									
6N1	Blue	6621	44	88	45	53	-6	...	1292
6N2	Top	7389	52	71	70	67	4	551	143
6N3	Green	6598	44	83	57	56	-2	...	1324
6N4	Bottom	6159	52	85	51	50	-5	238	118
6N5	Red	5699	45	79	42	43	-8	2283	1127
6N6	Top	5355	52	73	37	37	-10	162	103
6N7	Green	5030	51	66	30	31	-13	1492	990
6N8	Bottom	4778	52	61	25	26	-14	128	92
6N9	Blue	4930	51	49	41	14	0	1511	1228
6N10	Top	4727	52	44	39	10	-1	123	111
6N11	Green	4541	51	39	37	4	-3	1177	1124
6N12	Bottom	4428	52	35	38	0	-3	109	107
6N13	Red	4331	52	29	40	354	-4	1090	1130
6N14	Top	4903	80	71	62	37	-13	253	94
6N15	Green	4404	73	60	50	25	-16	2202	865
6N16	Bottom	4105	80	52	42	18	-17	123	79
6N17	Blue	3865	80	44	34	10	-18	1270	756
6N18	Top	3746	80	38	31	4	-16	105	73
6N19	Green	3617	80	31	25	357	-17	983	718
6N20	Bottom	3546	80	26	21	351	-16	91	69
6N21	Red	3501	80	20	17	345	-16	889	697
6N22	Top	3498	80	14	15	340	-15	86	69
6N23	Green	3522	80	8	15	334	-14	880	706
6N24	Bottom	3584	80	3	18	328	-13	88	71
Mariner 7									
7N1	Blue	8725	37	79	44	9	-5	...	1767
7N2	Top	9766	43	58	75	13	20	...	201
7N3	Green	9118	44	67	67	59	12	...	2144
7N4	Bottom	8492	44	75	59	5	4	401	162
7N5	Red	7995	44	82	52	3	-2	...	1598
7N6	Top	7552	44	88	46	359	-7	269	144
7N7	Green	7136	44	85	41	356	-12	3143	1406
7N8	Bottom	6774	44	80	36	353	-17	203	130
7N9	Blue	6443	44	74	31	350	-21	1989	1272
7N10	Top	6693	35	39	48	33	-54	168	190
7N11	Green	6381	35	38	45	27	-57	1650	2025
7N12	Bottom	6095	35	36	43	21	-61	149	159
7N13	Red	5886	35	34	43	17	-65	1512	1690
7N14	Top	5662	35	31	42	9	-68	142	143
7N15	Green	5495	35	28	43	1	-71	1484	1513
7N16	Bottom	5318	35	25	43	349	-74	141	132
7N17	Blue	5195	35	21	45	334	-77	1549	1394
7N18	Top	5069	35	18	46	314	-77	148	124
7N19	Green	5013	35	13	49	291	-78	1837	1356
7N20	Bottom	4971	35	8	53	269	-75	172	124
7N21	Red	5337	80	76	66	354	-21	...	1066
7N22	Top	4818	80	66	56	346	-28	210	92
7N23	Green	4431	80	57	47	339	-34	1951	868
7N24	Bottom	4154	80	49	40	331	-38	132	80
7N25	Blue	3938	80	43	34	324	-42	1218	773
7N26	Top	3778	80	36	29	316	-44	104	73
7N27	Green	3656	80	31	24	308	-46	989	723
7N28	Bottom	3679	80	24	28	278	-41	94	77
7N29	Red	3633	80	19	26	291	-41	925	779
7N30	Top	3636	80	13	27	284	-39	89	78
7N31	Green	3660	80	8	28	277	-38	915	811

CRATERED TERRAIN

Mosaic of Seven Camera A Frames 6N9 Through 6N23

This series sweeps eastward (left to right) across the heavily cratered Martian equatorial regions from dark areas Margaritifer Sinus and oasis Oxia Palus through dark area complex Meridiani Sinus-Sabaeus Sinus with adjacent bright area Deucalionis Regio.

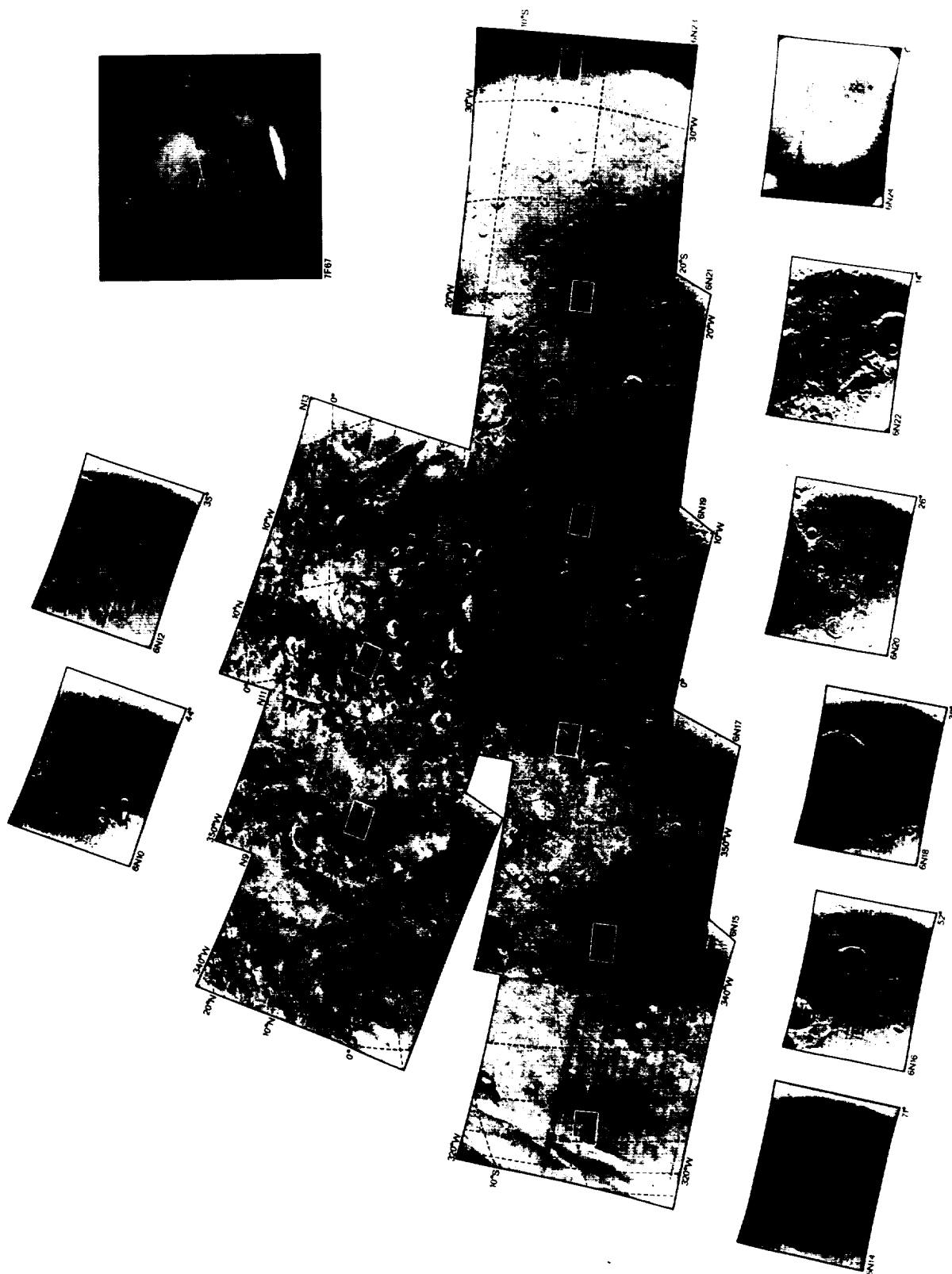
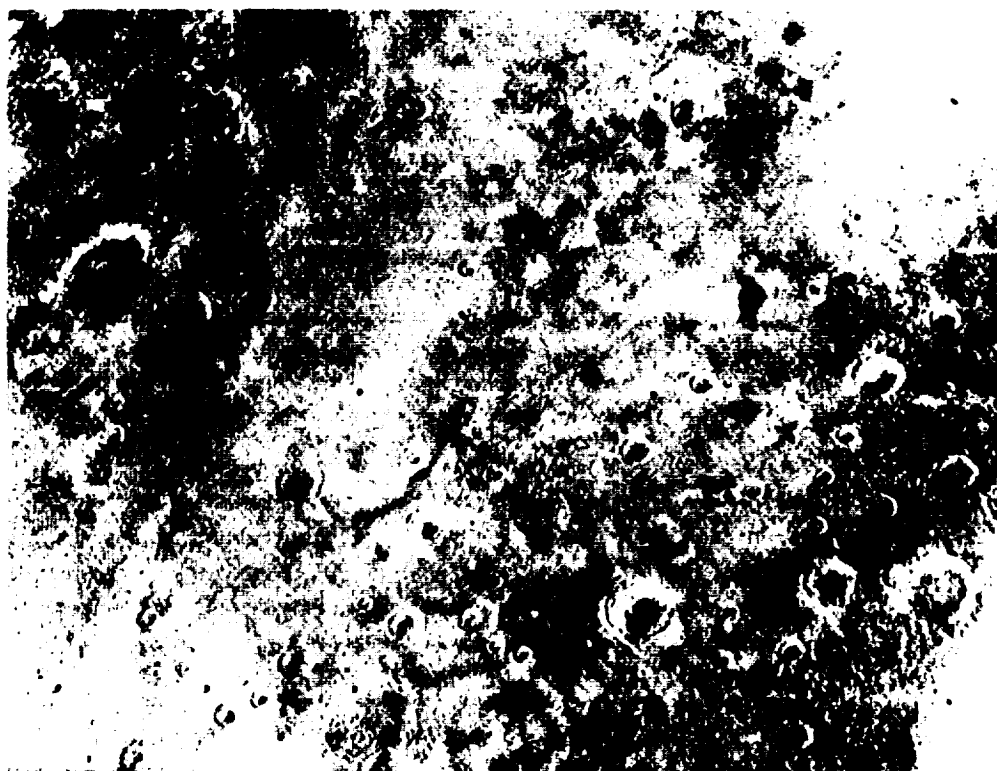
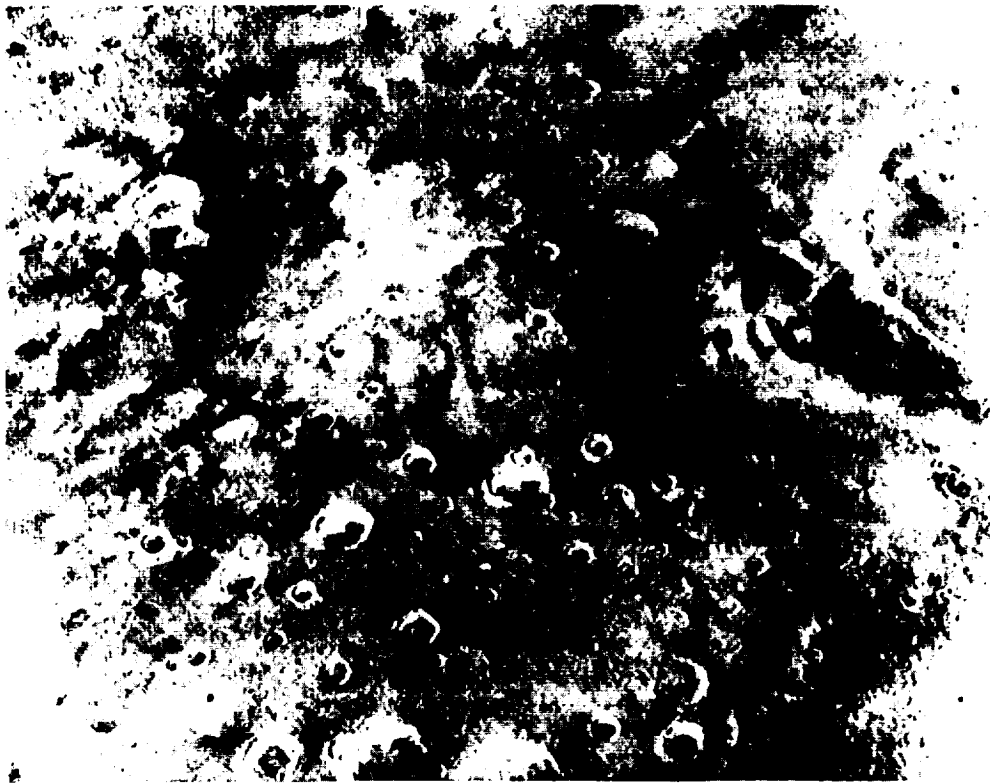


Fig. 32. Mosaic 6N9 through 6N23 (cratered terrain).



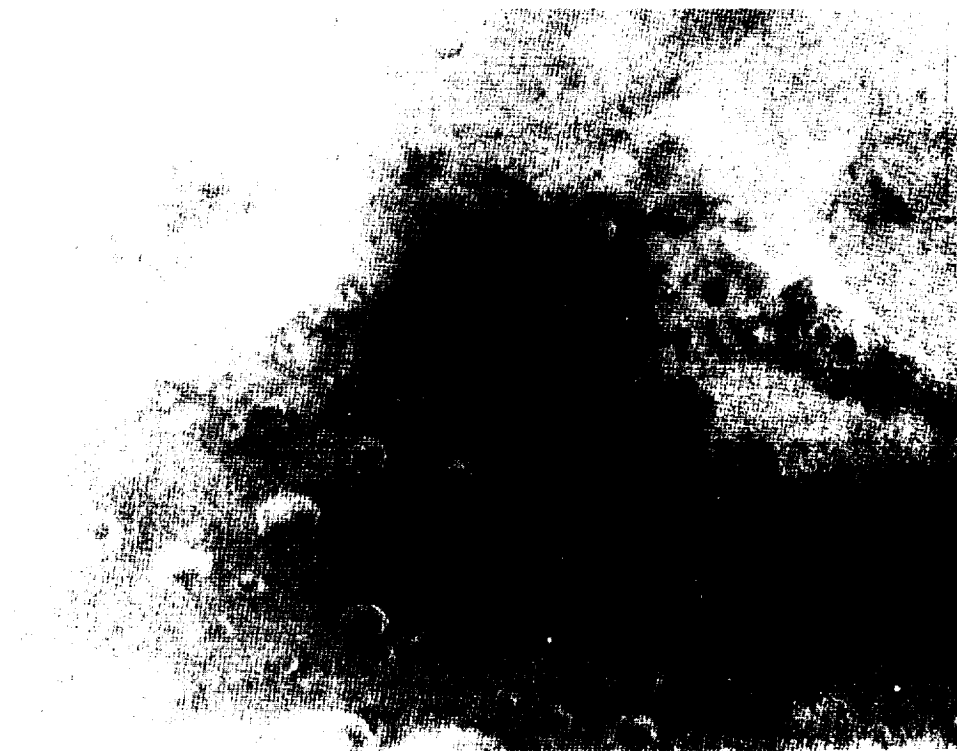
6N11 — Western side of prominent dark area Meridiani Sinus. Diffuse boundary or transition into bright area Thymiamata at left. Cratered terrain extends east-west across both areas.

Fig. 33. Near Encounter Frame 6N11.



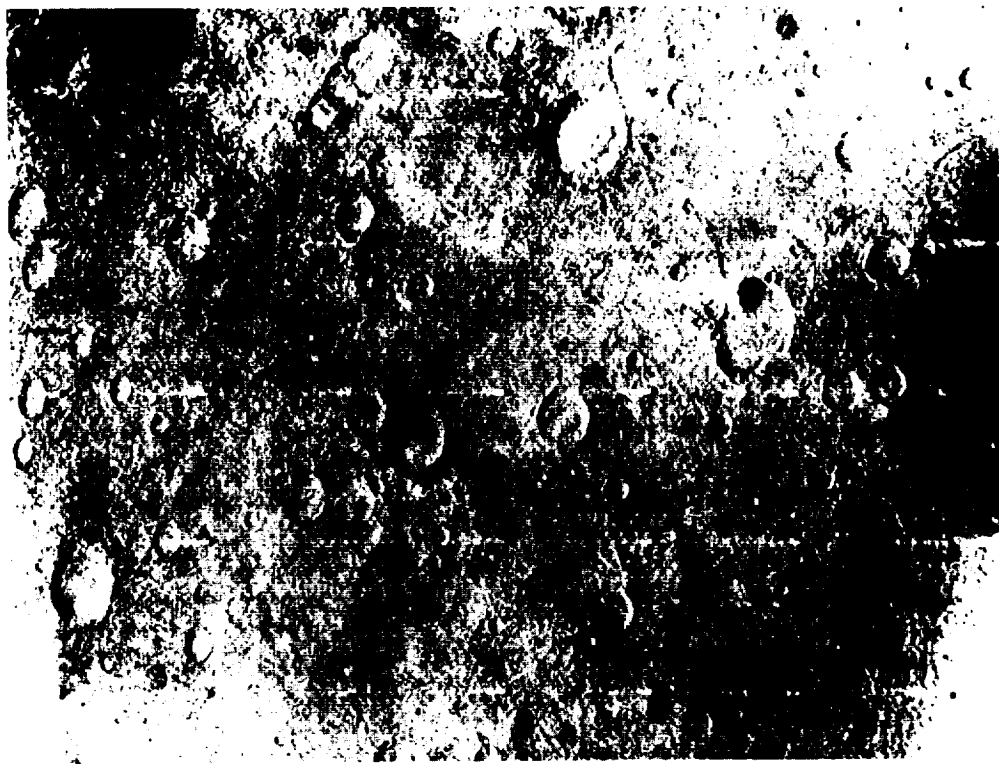
6N13 — Meridiani Sinus: its forked northern portion is viewed here in the Max-D version, processed to reveal details of the local topography. Note the asymmetric shading of craters and the irregular northeastern boundary of Meridiani Sinus. Part of 300-km crater Edom appears at far right.

Fig. 34(a). Near Encounter Frame 6N13 (Max-D version).



6N13 — Meridiani Sinus: In this photometric version, the large-scale albedo variations are visible.

Fig. 34(b). Near Encounter Frame 6N13 (photometric version).



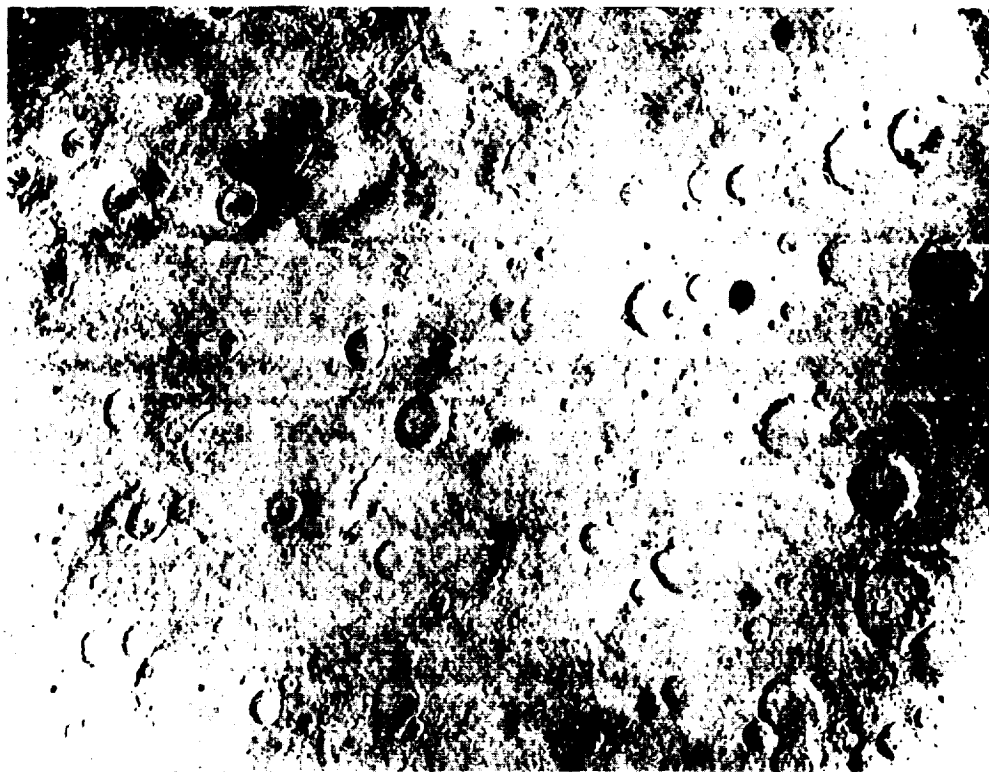
6N17 — Cratered terrain consisting mostly of flat-bottomed craters. The location of this frame contains parts of Margaritifer Sinus at left and the bright area Thymiamata at right. The large scale albedo variations have been suppressed in this Max-D version.

Fig. 35. Near Encounter Frame 6N17.



6N18 — Closeup view of a typical large flat-bottomed crater about 30 km across. The large crater shows some terracing, but no central peak. Location is south of Meridiani Sinus near longitude zero. Note the large grooved structure at bottom left.

Fig. 36. Near Encounter Frame 6N18.



6N19 — A multitude of flat-bottomed craters in the bright area Deucalionis Regio are clearly visible in the lower two-thirds of the picture. Dark area Meridiani Sinus appears in the upper third of the frame. Distinction between light/dark area does not show in this Max-D processed version of the picture.

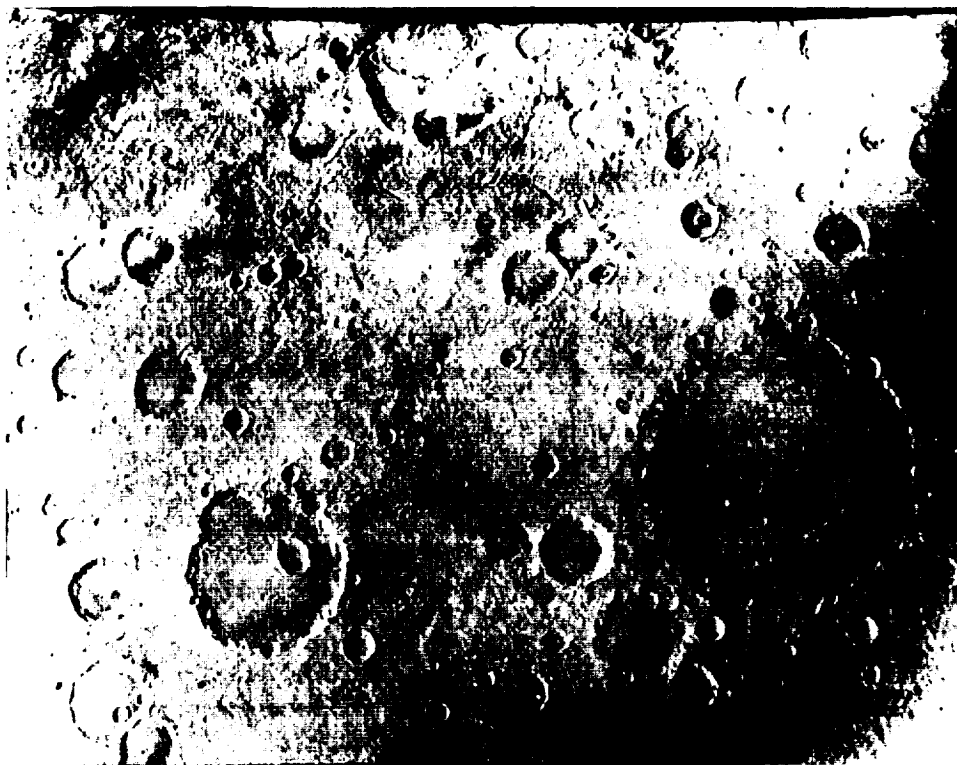
The craters have sizes ranging from a few km to about one hundred km across. Under the favorable low solar illumination angle, some large faint 'ghost' craters are discernible.

Fig. 37. Near Encounter Frame 6N19.



6N20 — Small bowl-shaped craters of various sizes. A double-ring, concentric structured 'ghost' crater is visible on the left. Faintly visible on the right is a low, irregularly sinuous ridge, oriented roughly north to south.

Fig. 38. Near Encounter Frame 6N20.



6N21 — This picture shows a continuation of the cratered terrain of frames 6N19 and 6N17, eastward over Deucalionis Regio, in the lower two-thirds of the picture, and Sabaeus Sinus in the upper third. Large flat-bottomed craters show up distinctly in the low sun. One crater is about 250 km across.

Approximately 250 flat-bottomed craters with diameters over 7 km were counted in the three frames 6N17, 19, and 21 for a size-frequency distribution analysis.

The boundary between light Deucalionis Regio and dark Sabaeus Sinus (barely visible in this Max-D picture) has a "diffuse" character, as in frame 6N19.

Fig. 39. Near Encounter Frame 6N21.



6N22 — Closeup view showing a 'smaller' flat-bottomed crater upon the rim and the irregular wall of the large 250-km crater seen in frame 6N21.

A number of very small bowl-shaped craters are also visible. From this frame and frame 6N20 a count was made of 104 craters with diameters over 0.7 km.

Fig. 40. Near Encounter Frame 6N22.

CHAOTIC TERRAIN

Mosaic of Four Camera A Frames 6N1 Through 6N7

The mosaic shows an overall view of the chaotic terrains, photographed by Mariner 6 in the equatorial regions of Mars. These terrains are irregularly shaped and irregularly distributed in the mixed light and dark area Pyrrhae Regio, with prongs extending into dark areas Aurorae Sinus to the west, Margaritifer Sinus to the northeast, and into light area Chryse to the north.

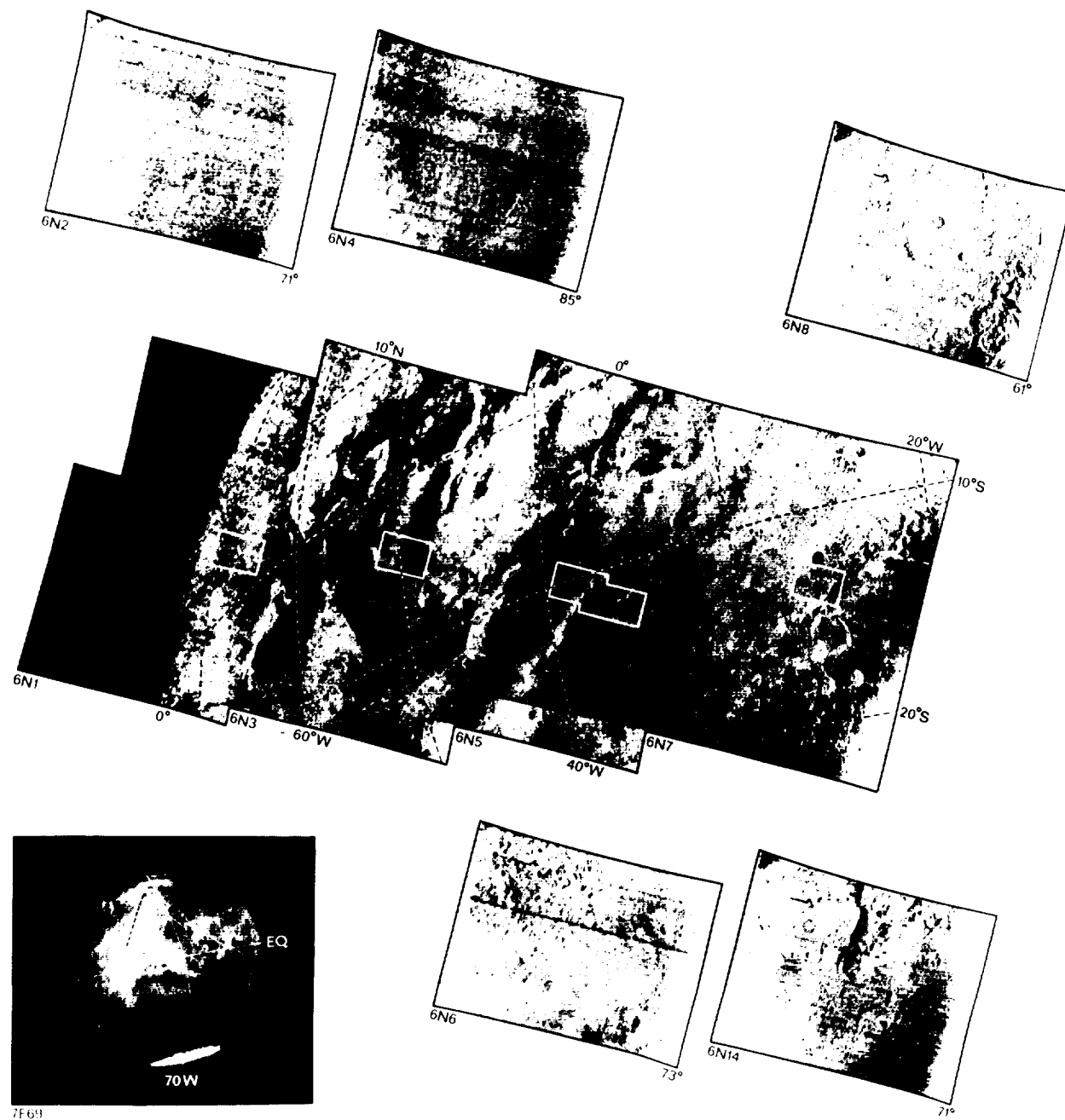


Fig. 41. Mosaic 6N1 through 6N7 (chaotic terrain).



6N3 — This picture is another limb view encompassing more territory eastward (left) into dark area Aurorae Sinus, where some chaotic terrain patches already appear amidst cratered terrain. Xanthe desert is shown toward the limb.

The heavy dark band is the residual image of the limb from a previous frame.

Fig. 42. Near Encounter Frame 6N3.



6N5 — Many irregular patches of chaotic terrain covering a sizable area are visible in this oblique view of Aurorae Sinus, with part of Pyrrhae Regio visible at the top right.

This region, in which chaotic and cratered terrains are intricately intermixed, is difficult to analyze geologically.

Fig. 43. Near Encounter Frame 6N5.

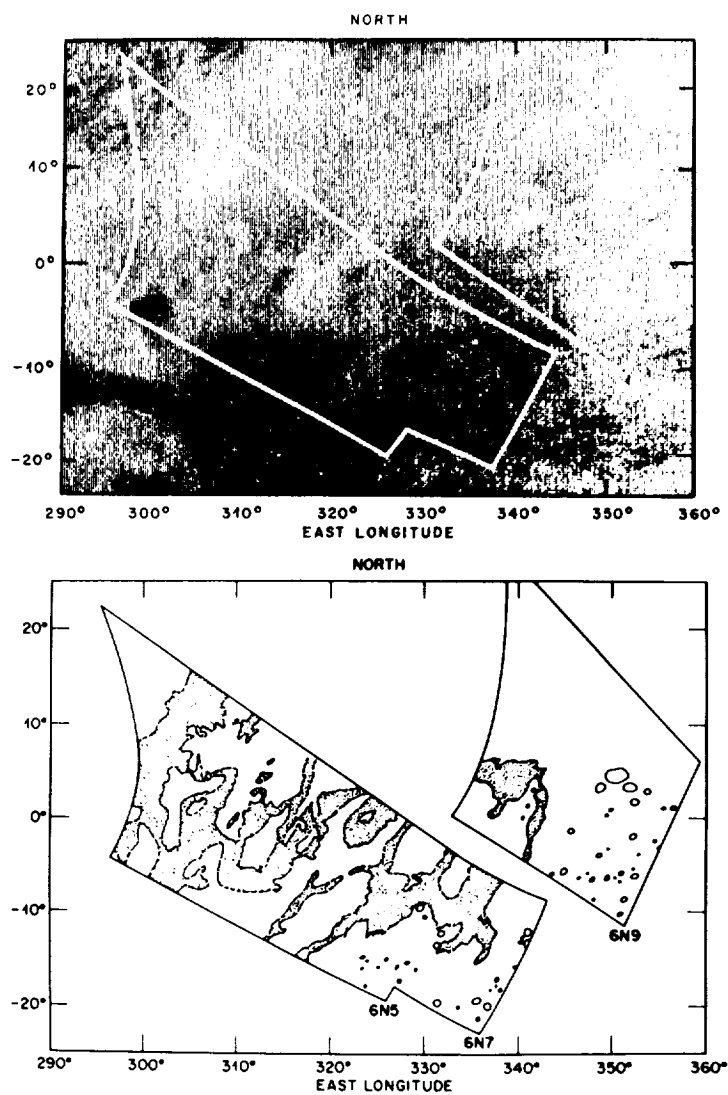
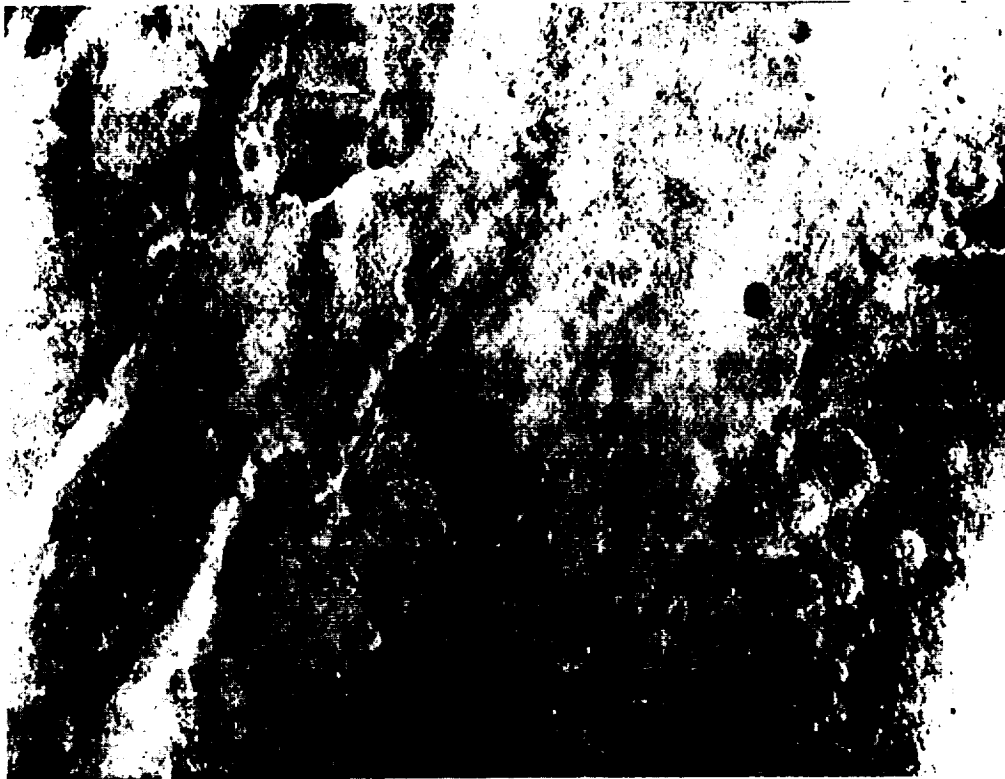


Fig. 44. Distributions of light and dark markings (top) and chaotic terrain (bottom) in equatorial region photographs 6N5, 7, and 9 (after Cutts et al., 1971).



6N6 — This picture is a high-resolution view of an area of chaotic terrain with display of its characteristic pattern of ridges and troughs.

Fig. 45. Near Encounter Frame 6N6.



6N7 — This shows the irregular but well-defined patches of chaotic terrain in Aurorae Sinus at left and Pyrrhae Regio at right. Note the abrupt vertical scarp shadow line at the top left. The remainder of the terrain is fairly well cratered with old, flat-bottomed craters.

For high-resolution frames of this area see 6N6 and 6N14, and 6N8, where the details of chaotic structure are strikingly revealed.

Fig. 46. Near Encounter Frame 6N7.



6N8 — A high-resolution view of the transition from cratered terrain to chaotic terrain. The transition to chaotic "displays all the characteristics of a slump zone on Earth, although scale is unusually large," Sharp et al. (1971b). Note the abrupt scarps at bottom right.

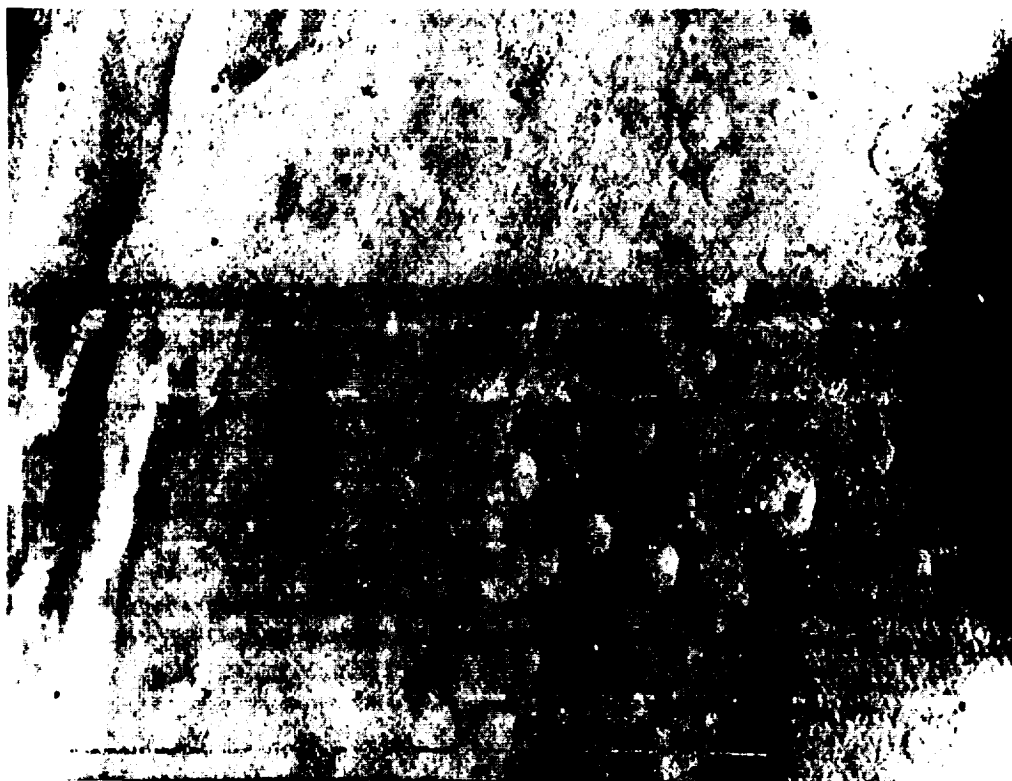
The cratered terrain has a rather large, old, flat-bottomed crater and many fresh-looking small bowl-shaped craters.

Fig. 47. Near Encounter Frame 6N8.



6N14 — High-resolution view of the "Chaos Valley" barely visible in frame 6N7. To quote Prof. Sharp (it) "looks like a feature which has extended itself headward and sidewise into cratered terrain" (Sharp et al., 1971b).

Fig. 48. Near Encounter Frame 6N14.



6N15 — This picture shows clearly defined brighter patches in the distance at left which are probably chaotic terrain across otherwise well-cratered terrain. Details of these patches cannot be seen because of highly oblique viewing.

This frame extends over much territory, including the base of Margaritifer Sinus, Pyrrhae Regio, and Aurorae Sinus at left. As many as five high-resolution B-frames were taken within it: 6N4, 6, 8, 14, and 16. Three of these (6N6, 8, and 14) unmistakably show some chaotic terrain.

Fig. 49. Near Encounter Frame 6N15.

FEATURELESS TERRAIN

Mosaic of Frames 7N21 Through 7N31

This mosaic depicts six A-frames spanning from the west limb, over the Meridiani Sinus dark band (7N21, left), bright strip Deucalionis Regio, Pandora Fretum, a variable patch, bright desert Noachis, dark well-cratered Hellespontus, and across featureless circular desert Hellas into evening terminator (7N31 at right). Maximum discriminability versions (Max-D) were used. Max-D brings out topographic detail at the expense of albedo contrast.

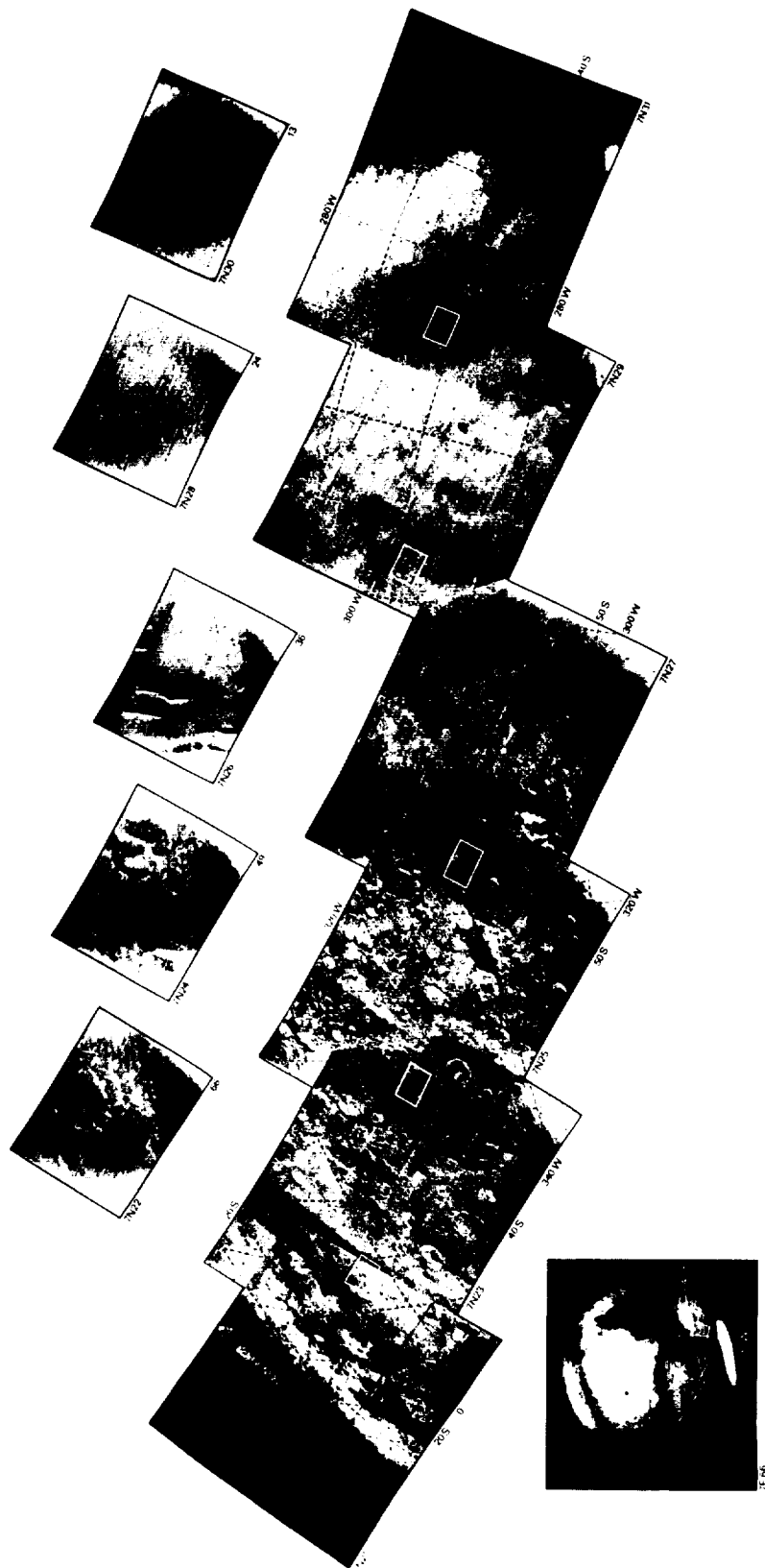
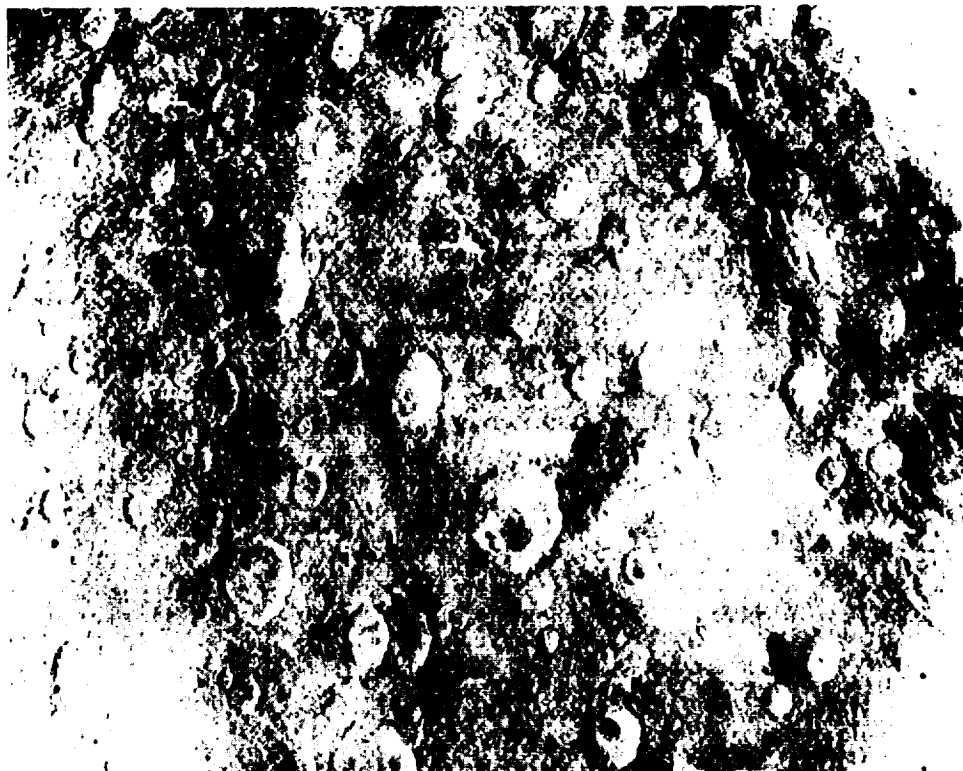


Fig. 50. Mosaic 7N21 through 7N31 (featureless terrain).



7N25 — This shows the heavily cratered dark area Hellespontus, bordered to the east by featureless Hellas, just discernible at the top right-hand corner. In the wide transition zone into Hellas, the craters not only become rarer, flatter, and fainter, but there exists a series of overlapping narrow linear ridges and scarps facing Hellas and parallel to its border. These features suggest definite crustal creep downward toward Hellas with a succession of abrupt drops in elevation.

Width of transition zone varies from 150 to 325 km. Length of ridges and scarps range from 20 to 90 km.

Fig. 51. Near Encounter Frame 7N25.



7N26 — Closeup picture of the conspicuous ridges and scarps in the transition zone from Hellespontus to Hellas. Length of ridges is about 40 km, while scarps, at bottom left, are shorter.

This local area of the transition zone is unusually poor in small craters.

Fig. 52. Near Encounter Frame 7N26.



7N27 — This shows the interior of Hellas is a monotonously smooth surface with only three small flat-floored craters visible, on its western edge.

The transition zone into Hellespontus on the west is irregularly defined along its Hellas edge, by an abrupt contrast from light (in Hellas) to dark in the transition zone. The contrast does not show up here in these Max-D versions used to enhance local topographic details. The scarps and ridges on the western, or Hellespontus, edge of the zone do stand out.

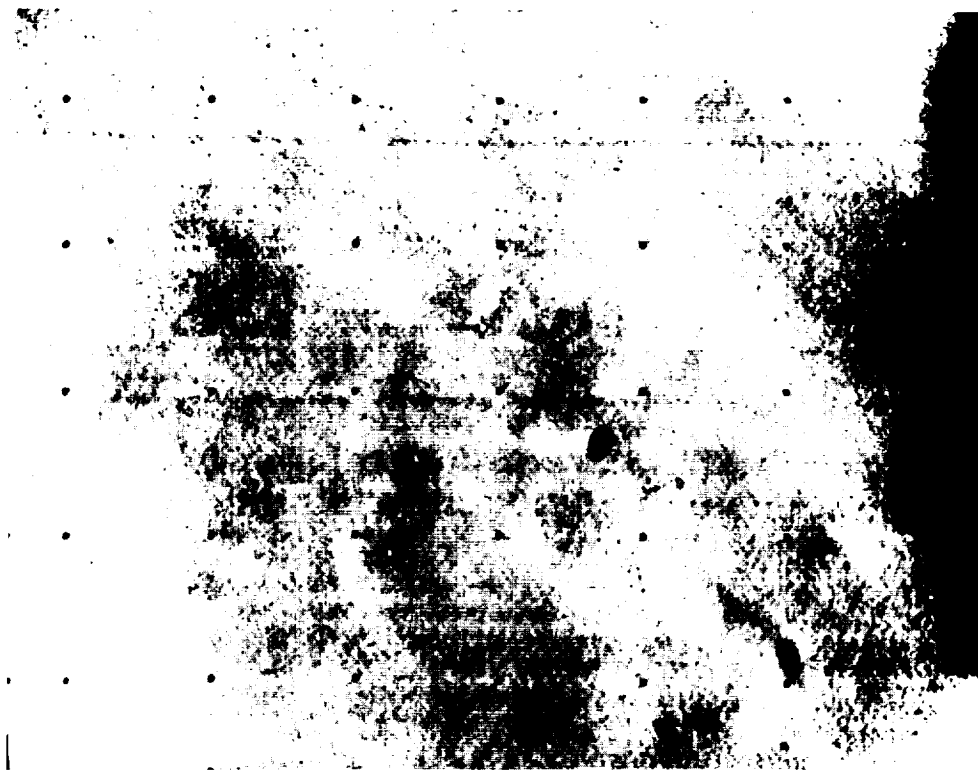
Flat-floored craters are present in the transition zone, but they gradually disappear as the zone slopes downward into Hellas.

Fig. 53. Near Encounter Frame 7N27.



7N28 — This high-resolution frame confirms the featureless terrain within Hellas. Resolution is about one-half km.

Fig. 54. Near Encounter Frame 7N28.



7N29 — This is another picture of the featureless central parts of Hellas.

Fig. 55. Near Encounter Frame 7N29.

ATMOSPHERIC HAZE (Limb Pictures)

Mosaic of Frames 7N1 and 7N3

This mosaic covers the highly oblique northwestern view of complex region, composed of dark fork Meridiani Sinus, bright channel Thymiamata, and dark oasis Oxia Palus. Due to incomplete erasure by the vidicon system, only the upper, or northern, portions of these areas appear in this mosaic. The bright desert Chryse is beyond, on the limb. See frame 7N2 for a magnification of the limb portion.

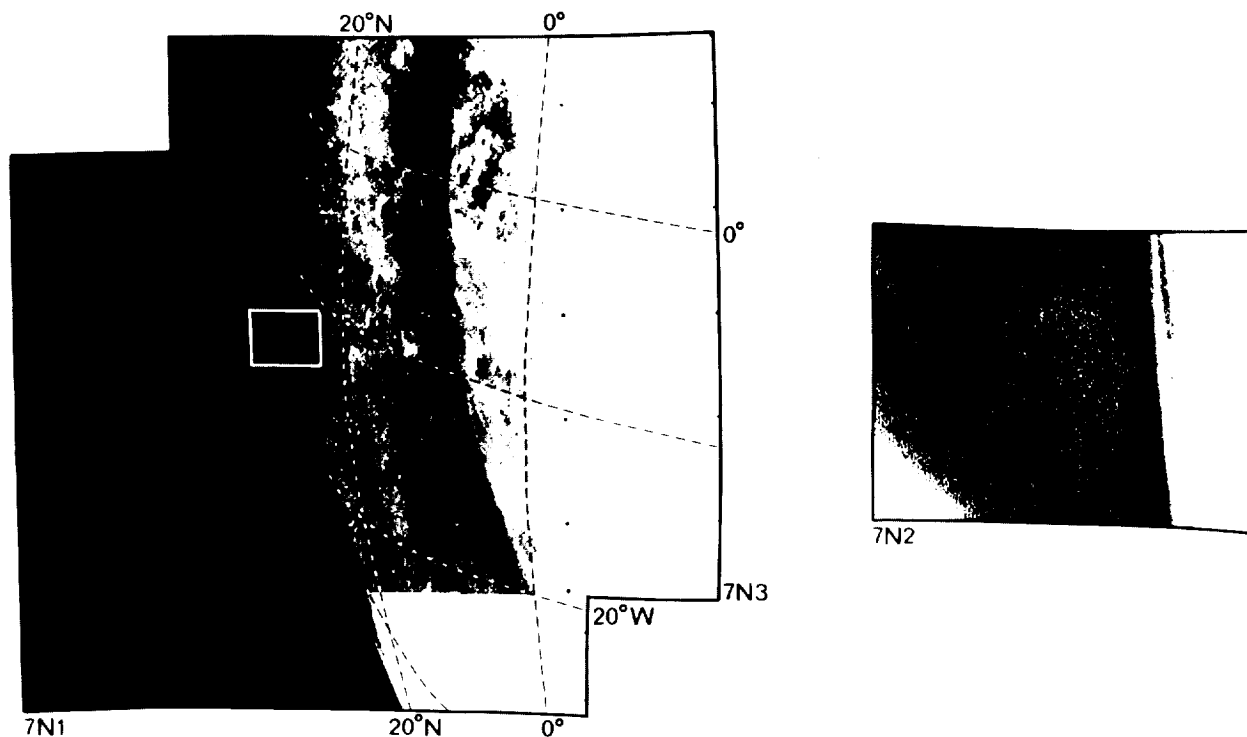


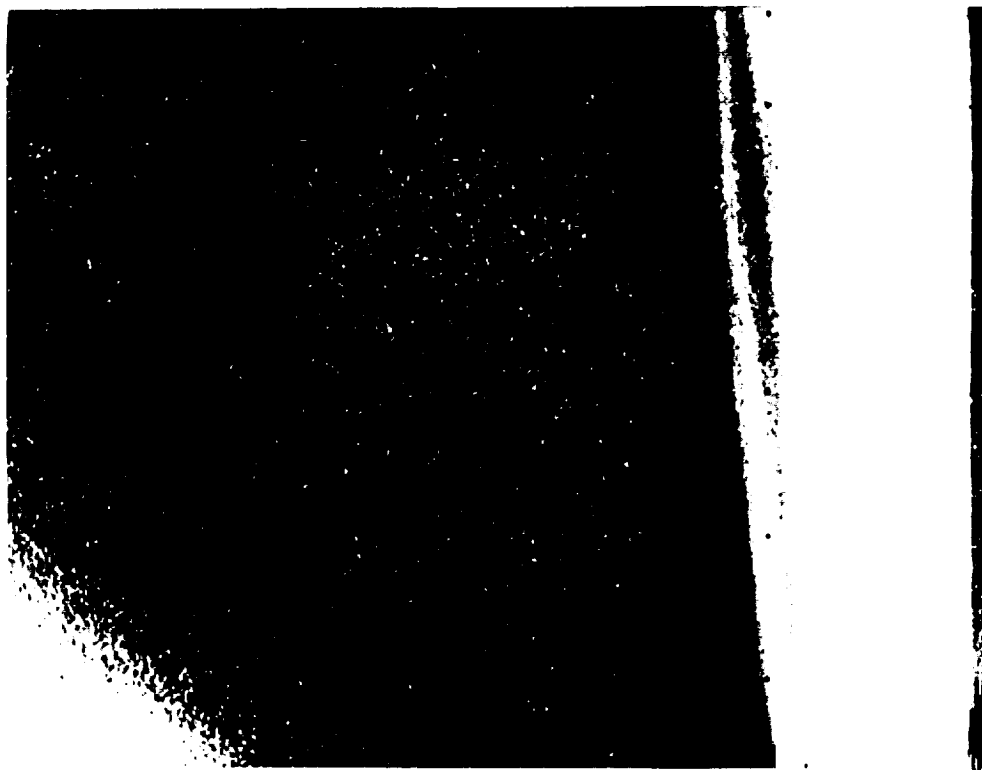
Fig. 56. Mosaic 7N1 and 7N3 (atmospheric haze).



7N1 — This is a northwest limb, blue-filter frame over Chryse desert (on limb), revealing a thin haze layer distinctly detached from the limb. Altitude of the base of the haze layer was estimated at about 5 km above the surface of the desert. Geometrical thickness of the haze is about 5 km (Leovy et al., 1971).

Photometric comparison of the brightness of this layer in three colors, using this blue-filter frame and 7N3 (green) and 7N5 (red), shows it to be essentially white, with an absence of blue coloring anywhere in the layer.

Fig. 57. Near Encounter Frame 7N1.



7N2 — High-resolution view of the detached thin haze layer appearing in frames 7N1 and 7N3. Under even higher magnifications and special processing, the layer reveals its multilayered structure of at least three layers (Leovy et al., 1971).

Fig. 58. Near Encounter Frame 7N2.

DARK AND LIGHT AREAS (Meridiani Sinus Complex)

Mosaic of Three A Frames 7N5, 7N7, and 7N9 (Photometric Version)

This mosaic shows an overall oblique view of the equatorial region of prominent dark area Meridiani Sinus, which forms the enlarged hand-like end of the long dark arm Sabaeus Sinus, alongside the Martian equator. (Limb orientation is about NNW, toward Mare Acidalium.) Seen here at 8000-km slant range, Meridiani Sinus appears well cratered, not only within, but across its unusually varied boundary.

The light area Edom, which appears on maps as a round notch at the corner of Meridiani Sinus and Sabaeus Sinus, turns out to be a very large, bright-floored, flat-bottomed crater. See top right portion of frame 7N9. Crater wall defines a sharp boundary between light and dark areas, suggesting topographic control of the albedo, with the light area at lower elevation (Cutts et al., 1971).



Fig. 59. Mosaic 7N5, 7N7, and 7N9 (dark and light areas).



7N5 — A limb picture. A sharp detached haze layer appears in other versions. Prominent dark area Meridiani Sinus is well cratered. The craters display remarkable albedo patterns with light markings on their south-facing inner slopes. Note the isolated, dark-floored craters in neighboring bright areas also. The crater complex projecting from top left, not far from the limb, is the "oasis" Oxia Palus.

Fig. 60. Near Encounter Frame 7N5.



7N6 — This shows a high-resolution view of the craters in the middle of Meridiani Sinus. Note their asymmetric shading (not due to local highnoon sun), an aeolian deposition process of the light material inside dark-floored craters is suggested here.

Fig. 61. Near Encounter Frame 7N6.



7N7 — Meridiani Sinus is shown slightly more to the east than in frame 7N5. The dark arc is a residual image. West of the crater Edom (just appearing at right) there is a bright area encroaching erratically into the main body of Meridiani Sinus. Note that its boundary is very sharp as well as highly irregular, in that "small dark outliers" are found on the bright side, which has variable albedo (see Cutts et al., 1971).

Fig. 62. Near Encounter Frame 7N7.

SOUTH POLAR CAP

Mosaic of Frames 7N11 Through 7N19

This mosaic is presented in the two computer-processed versions. The photometric version (without AGC), Fig. 63 shows the actual brightness of the South Polar Cap's white expanse against the bare ground surrounding it. Craters are visible along its edge and in its interior, where floors appear darker, although frost-filled. The grid lines of latitude and longitude permit location of the South Pole and show that the cap extends northward beyond 60°S.

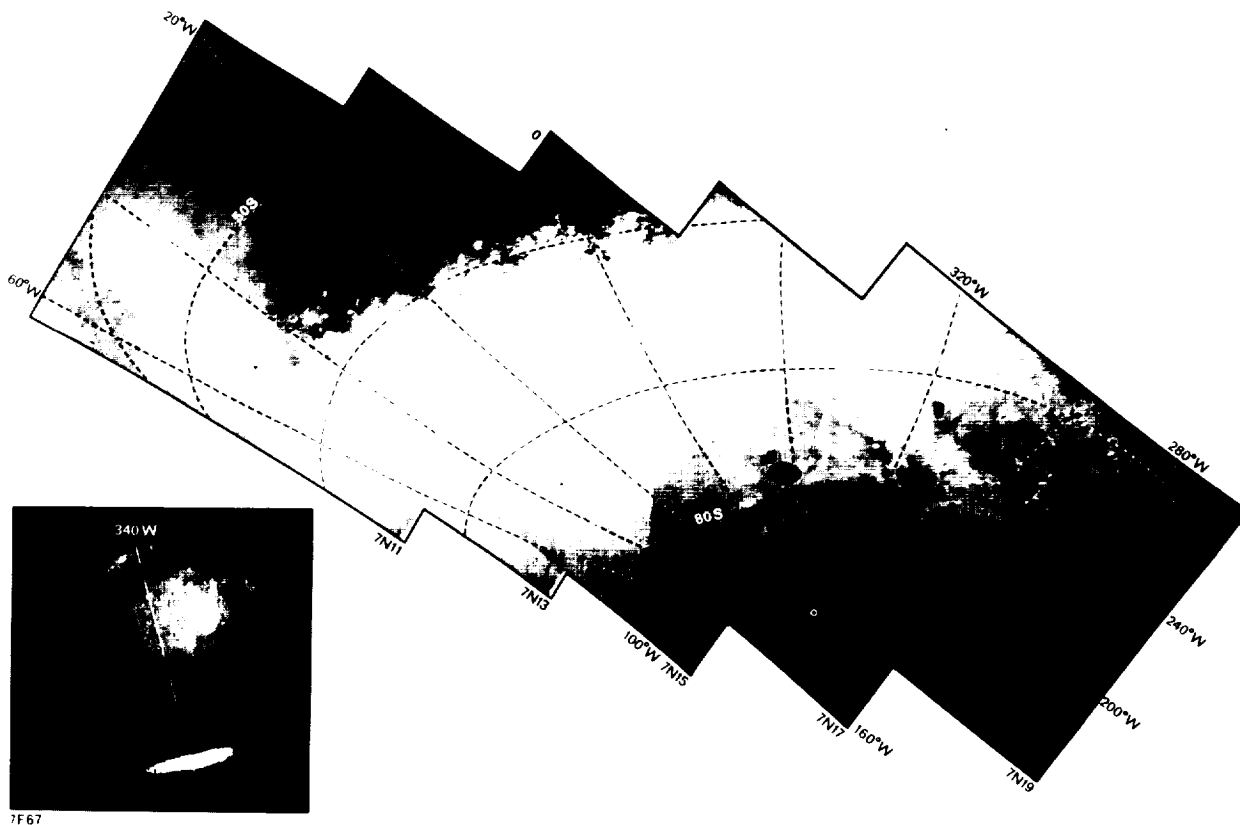


Fig. 63. Mosaic 7N11 through 7N19 (photometric version).

The maximum discriminability (Max-D) version mosaic (with AGC), Fig. 64 reveals, in a spectacular way, an intricate wealth of detail across the cap. Besides craters, there is evidence of a surprising variety of forms, due to both frost and underlying ground.

All Max-D versions of the polar cap edge show an unfortunate black band artifact which is not to be interpreted as the traditional dark polar collar. When the AGC effect is removed, as in the photometric version, there is no suggestion of it.

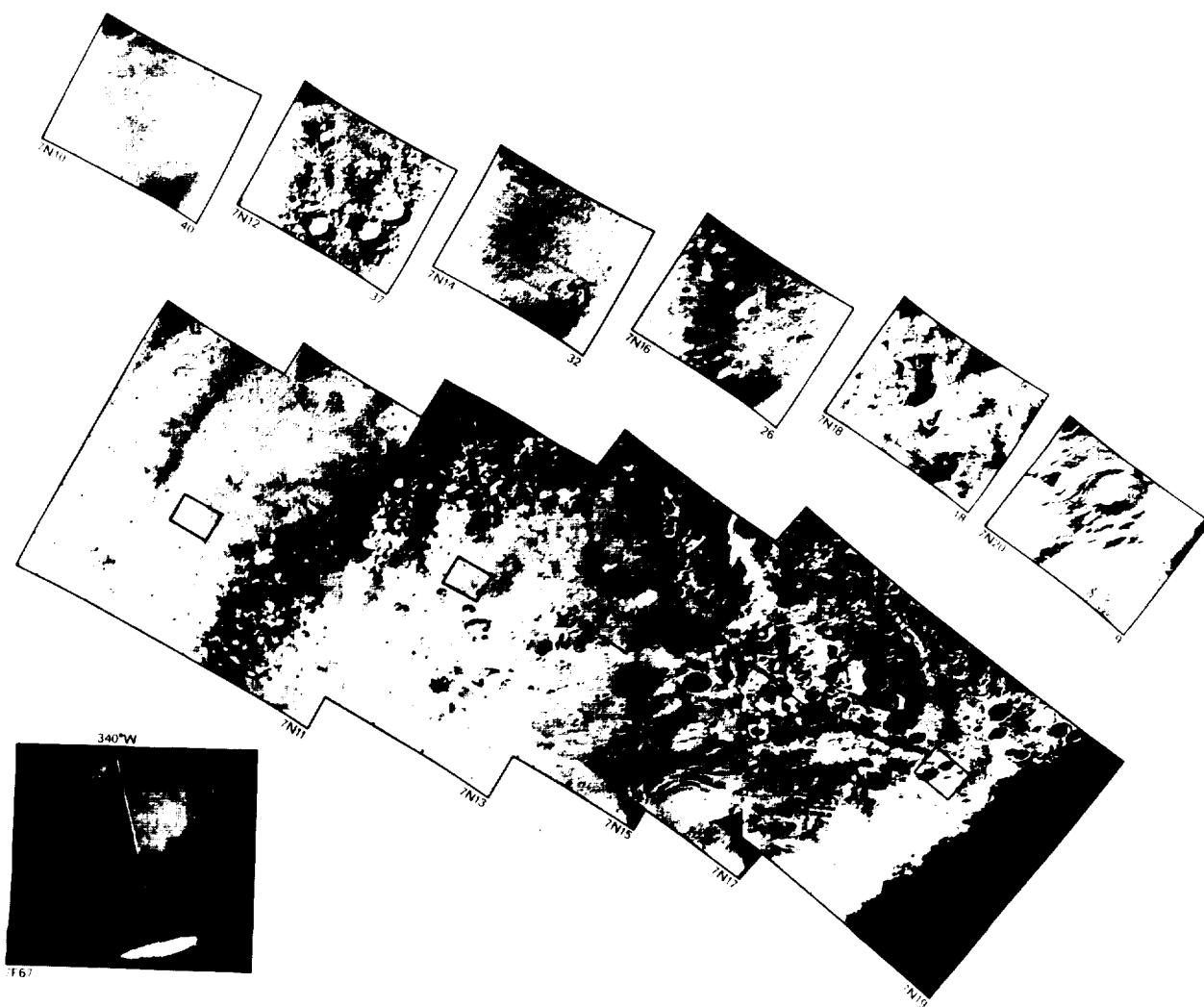
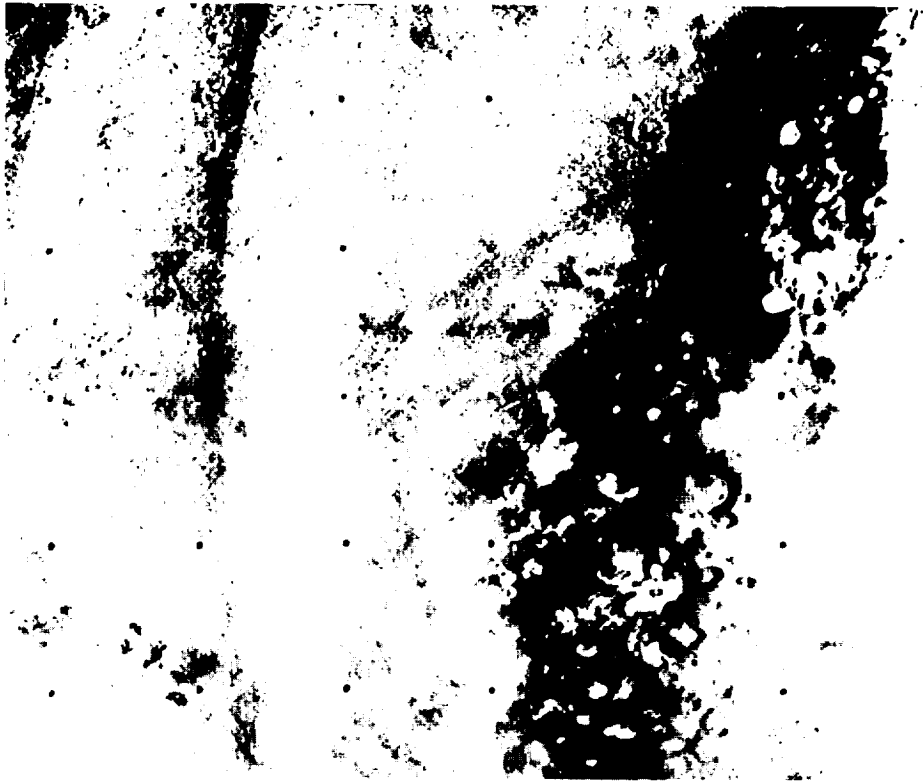


Fig. 64. Mosaic 7N11 through 7N19 (Max-D version).



7N11 — The extra-marginal edge of the South Polar Cap is best displayed on the west side of this wide-angle frame. The craters are apparently as abundant and of similar shape and size, to those elsewhere on Mars, where cratered terrain is prevalent. Note the presence of the black band artifact, which is absent in the photometric version (Fig. 65b).

Fig. 65(a). Near Encounter Frame 7N11 (Max-D version).

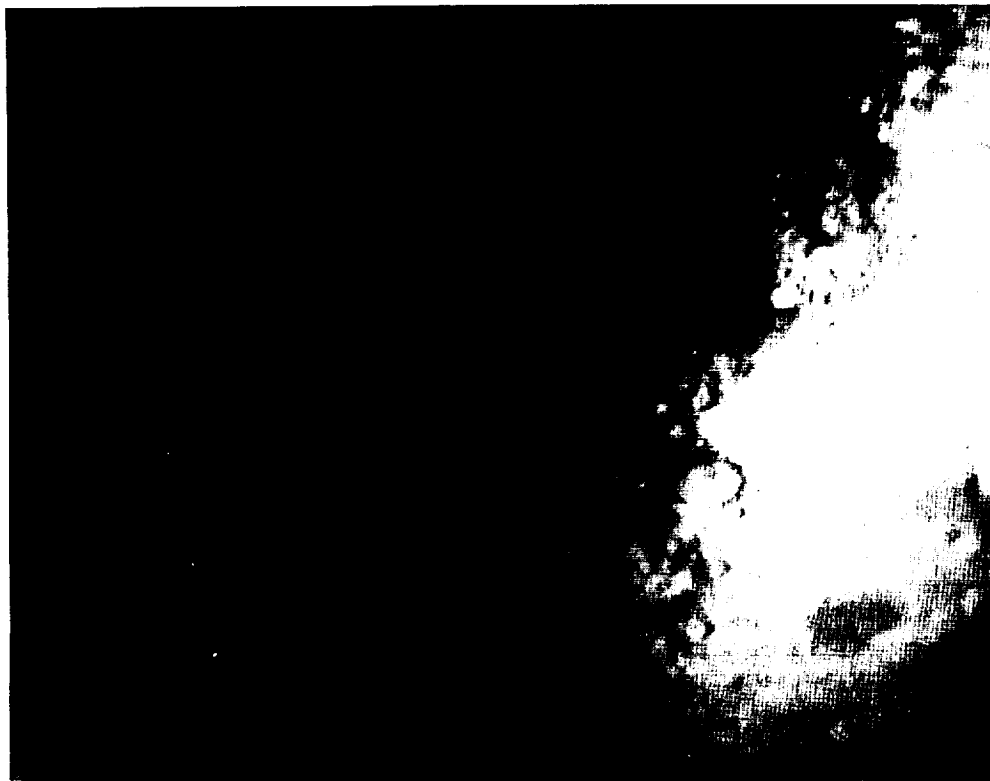
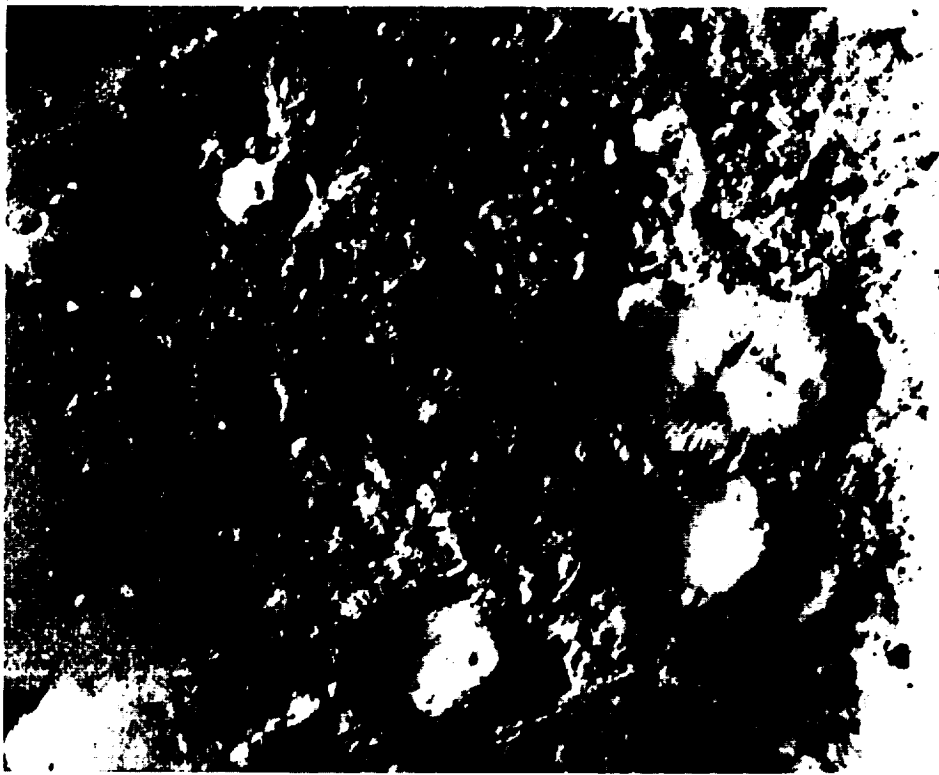


Fig. 65(b). Near Encounter Frame 7N11 (photometric version).



7N12 — This shows a closeup of a portion of the outer-marginal zone of the South Polar Cap, located in the dark band artifact mentioned earlier. Craters within this zone appear grotesquely distorted as a result of the unusual combination of low solar illumination and frost enhancement.

The brilliant patches are frost accumulations on portions of crater bottoms and on south-facing slopes which are more protected from solar rays.

Fig. 66. Near Encounter Frame 7N12.



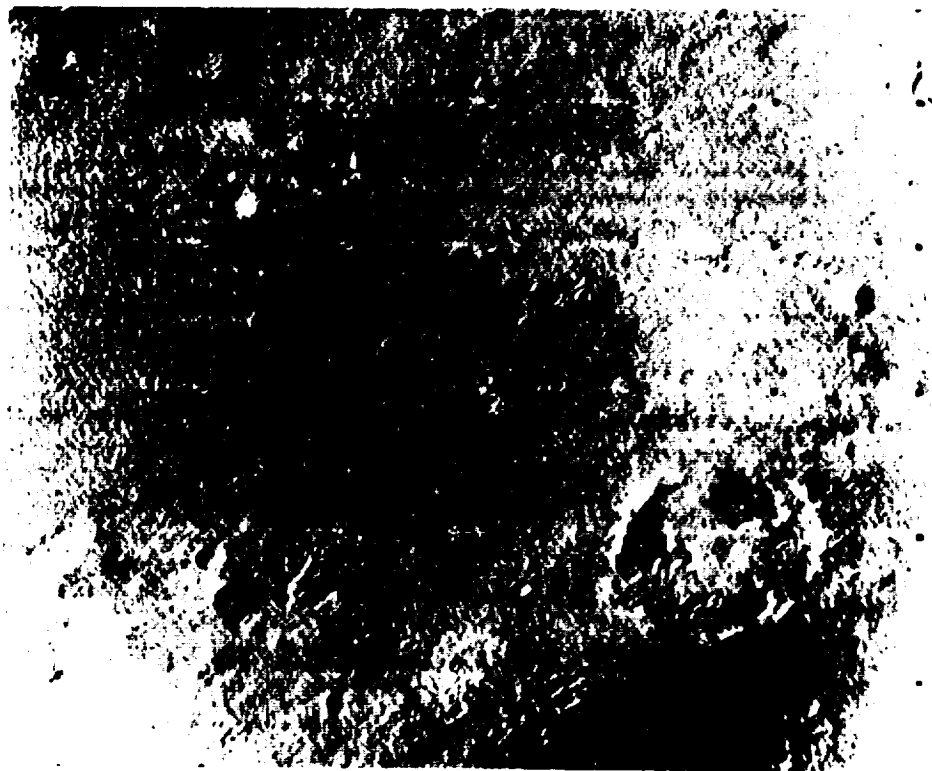
7N13 — The edge of the polar cap is shown again in this frame, as in frame 7N11, and also much more of the interior of the cap, where the frost layer becomes thick rapidly. Outlines of frost-filled craters are quite recognizable, but new unfamiliar forms make their appearance. See frame 7N14 closeup.

Note again along the edge of the cap how craters have their south-facing slopes covered with frost, while their north-facing slopes may be bare, due to solar exposure.

Fig. 67(a). Near Encounter Frame 7N13 (Max-D version).



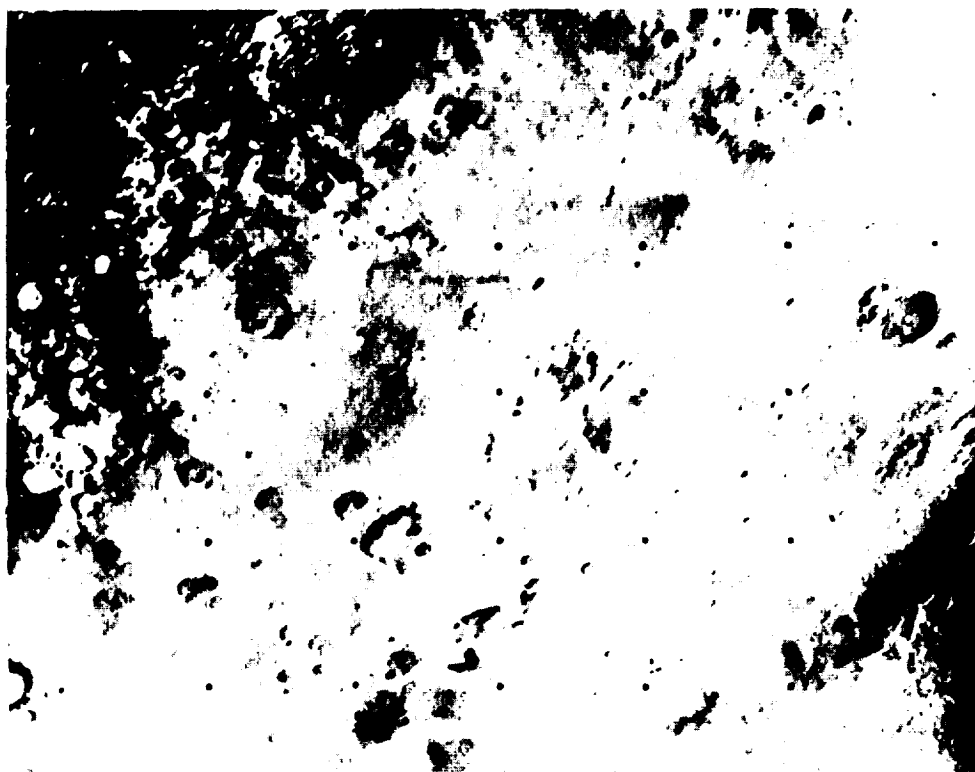
Fig. 67(b). Near Encounter Frame 7N13 (photometric version).



7N14 — This polar cap interior view shows a surprising etch-pit pattern developed within a frost-filled crater, humorously named the "elephant's footprint."

Frost cover in this narrow-angle frame otherwise appears remarkably even, except for the display of some small subdued features of positive relief, which are characteristic of the polar cap interior, as are the etch-pit depressions.

Fig. 68. Near Encounter Frame 7N14.



7N15 — This picture shows the portion of the polar cap interior cut across by the zero meridian. The marginal zone of the cap, top left, borders *Depressio Hellespontica*, well known as one of the areas where the "wave of darkening" starts in southern spring. The interior of the cap with continuous frost cover displays three types of features: craters of various sizes, irregular depressions called 'etch pits', and parallel features called 'beaded lineations'.

The etch pits are in the center. Note their lighter rims and somber crater-like floors of irregular, angular outline. The beaded lineations, to the south, are short alignments in WNW direction connecting tiny nodes. Such features may be the result of wind-drifted and scoured snow.

Fig. 69(a). Near Encounter Frame 7N15 (Max-D version).

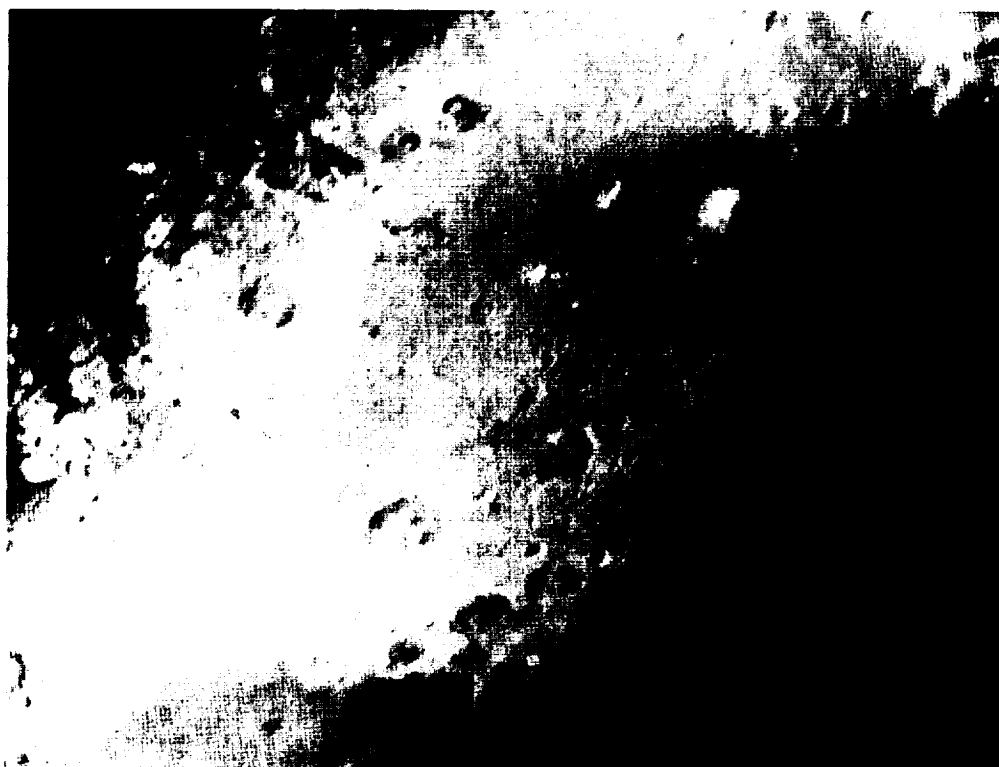
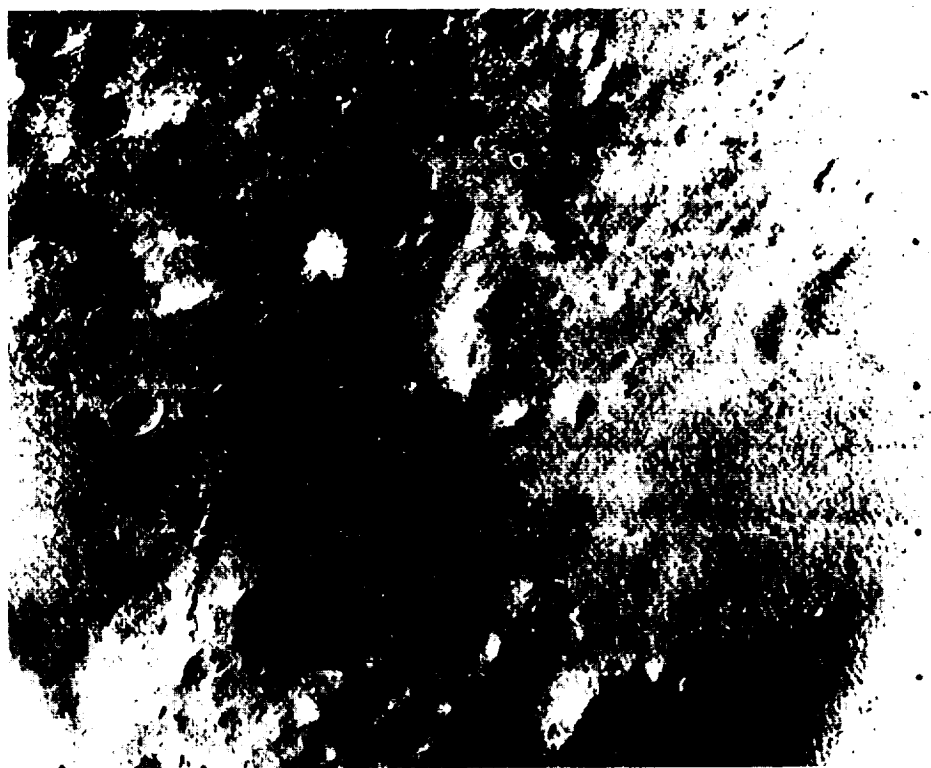
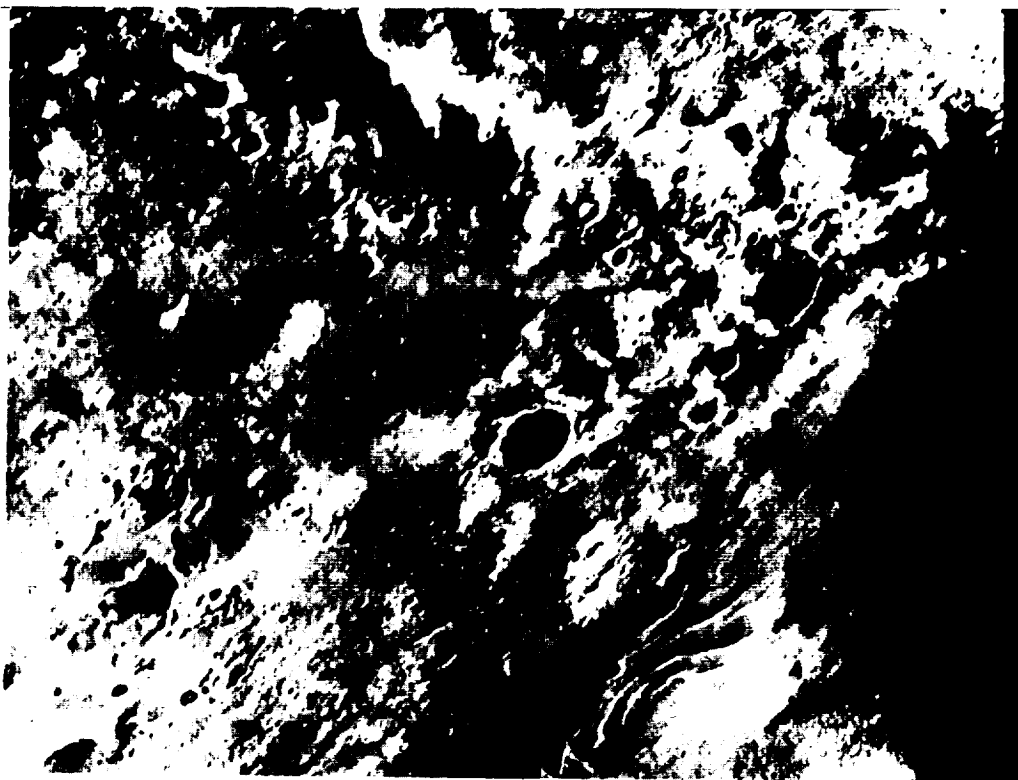


Fig. 69(b). Near Encounter Frame 7N15 (photometric version).



7N16 — This closeup picture shows the rather uniform frost coating of the cap interior. Local relief is very well evidenced by low solar illumination. Regions of positive relief are present, very few small craters are seen, and there are some shallow, depressed regions with irregular boundaries.

Fig. 70. Near Encounter Frame 7N16.



7N17 — Here is another view of the polar cap interior. The same general appearance, with unusually bright crater rims and somber floors, and etch pits are shown, as in frame 7N15. Also displayed in the interior are isolated, irregularly shaped patches and bands of unusual brightness (at top center and right), which must be the result of local topography and meteorology.

The central polar region appears in the lower right part of the frame, with eye-catching, long sinuous lineations, roughly concentric on the South Pole and spreading eastward. These may be up to 300-km long and 10-km wide. Note the sharp buckle of one. These enigmatic lineations are probably surface features and not clouds, because of their sharp boundaries, shape, shading, and distinct shadows. They may be troughs, ridges, or scarps, composed wholly of snow or ice combined or not with rock debris (see Sharp et al., 1971a).

The central polar region is also characterized by paucity and faintness of craters and the unusual smoothness of its snow or ice cover, which is probably a rather thick layer at least tens of meters deep.

Fig. 71(a). Near Encounter Frame 7N17 (Max-D version).

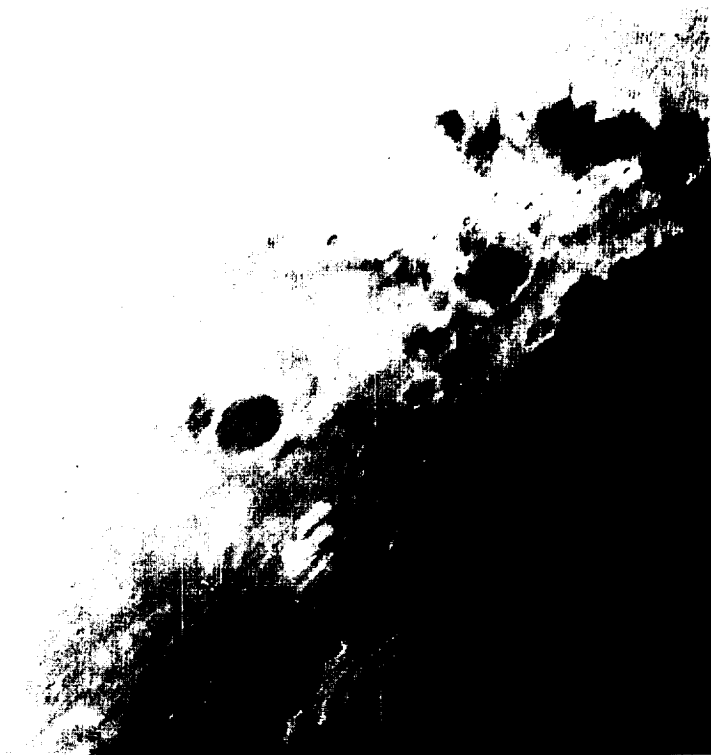
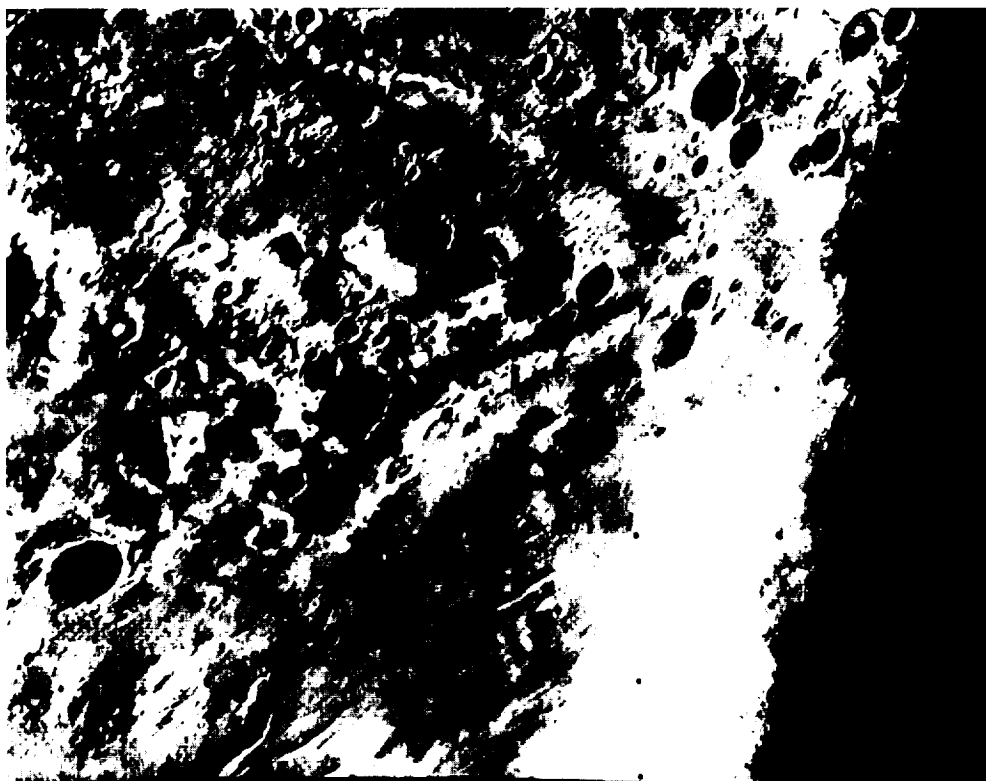


Fig. 71(b). Near Encounter Frame 7N17 (photometric version).



7N18 — This closeup shows three large (~50 km diameter) crater forms under the thick frost cover, taken well within the cap interior not far from the central region. The striations in the frost accumulation suggest the effect of persistent winds blowing predominantly in one direction. The presence of the three small craters, probably bowl-shaped, indicate that frost thickness cannot be too great.

Fig. 72. Near Encounter Frame 7N18.



7N19 — Again the polar cap interior and central regions are shown, as in frame 7N17. Sunset terminator is at the right. The linear and blotchy features are the same as in frame 7N17.

A pair of rather large craters forming the "giant's footprint" can be found in the center right among the many varied craters outlined by frost. Crater abundance of the cap interior is high in the northeast corner, as high in fact as in the most heavily cratered terrains photographed. A few craters in the left part of the frame have "small white central dots suggestive of central peaks or an unusual accumulation of frost."

The central polar region is best seen in this frame and frame 7N17. "Its boundary is most clearly defined in the central and eastern part of frame 7N19 as an abrupt, irregular, crater-scalloped arc with some vertical relief." (Quotations from Sharp et al., 1971a).

Fig. 73(a). Near Encounter Frame 7N19 (Max-D version).

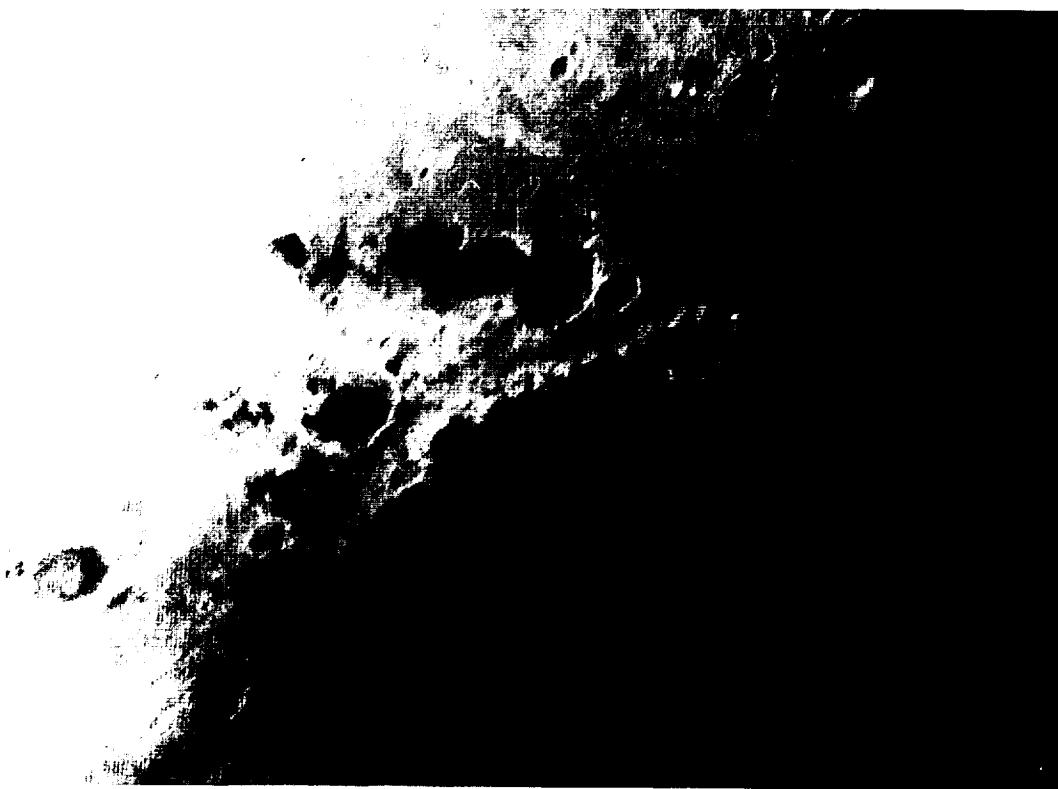


Fig. 73(b). Near Encounter Frame 7N19 (photometric version).



7N20 — This shows a high-resolution oblique view of the crater pair, forming the "giant's footprint." The irregularly ridged arch of the footprint is part of the boundary separating the central polar region (south) from the polar cap interior (north).

The Sun was low, only about 8° above the horizon, bringing out all details in this truly unusual view over the Martian South Cap.

Fig. 74. Near Encounter Frame 7N20.

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*Material is physically located behind new Section 4.2, page 45, dated February 1, 1972.

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4. OBSERVATIONAL PHENOMENA

INTRODUCTION

This section of the Mars Scientific Model includes discussion of many of those aspects of Mars which were originally discovered by direct visual observation. Section 4.1 encompasses discussion of such persistent, but often changing, phenomena as the clouds and hazes, while Section 4.2 is devoted to phenomena which change seasonally, such as the polar caps and the so-called "wave of darkening." There is a seasonal character to cloud activity which is also discussed in Section 4.2. It is hoped that a third section can be added at some future date to provide a discussion of the many secular changes in the Martian surface noted during the past 100 years.

More than brief mention of these phenomena is important in order to convey a proper appreciation of Mars as a dynamic, changing planet. This perspective is often lost in the presentation of quantitative data and simplified theoretical models. Yet, the very transitory nature of these phenomena has made quantitative study from Earth so difficult as to be practically nonexistent. It has resulted in fuzzy, subjective descriptions such as "violet layer," "blue clearing," "wave of darkening," etc., which have no root in quantitative physical study. The following sections are important primarily as a preliminary taxonomy based upon remote observation. The observations are of sufficient difficulty that some of them will prove partially fallacious, while attempts at physical explanation are at best tentative hypotheses. Nevertheless, this tentative data is the product of 100 years of labor and does offer an extended time base within which the new physical studies can be better understood. Therefore, the following information should be treated with reservation but not simply rejected.

4.1 CLOUDS AND HAZES

INTRODUCTION

Two types of Martian clouds are always distinguished by ground-based observers, white clouds, and yellow clouds. Many observers also recognize a distinct class of blue clouds, seen only in blue or violet light and distinct in properties and behavior from the white clouds. White clouds in turn exhibit several distinct types of behavior, and some of the so-called "clouds" may not be clouds at all but rather surface frost. Attempts at physical understanding of Martian cloud morphology are primitive at present, and many traditional "explanations" are subject to question by the Mariner series of Mars probes. Such is the class of phenomena discussed in this section.

4.1.1 DATA SUMMARY

The Violet Layer

The violet layer, sometimes called the blue haze or violet haze, is a high altitude atmospheric layer of submicron-sized particles hypothesized to explain the lack of contrast observed on Mars in blue and violet light. In fact, much of this lack of contrast is an intrinsic property of the surface material, and only remains a part of contemporary Martian theory because of the apparent need to explain the "blue clearing" phenomenon.

Blue Clearing

Generally, Martian surface detail can only be observed at wavelengths of 4500 Å or longer.

However, at times (with a transition period of about a day), the atmosphere of Mars becomes clear enough for a period of one or more days for surface detail to be seen clearly at wavelengths of 4250 Å or less. This "blue clearing" of the Martian atmosphere is attributed to a temporary dissipation of the violet layer (by those who believe in the violet layer).

White Clouds

White clouds are those which can be photographed at short wavelengths, but disappear in red or infrared photos. Sometimes an added distinction is made for certain "blue clouds" based upon behavior and polarization properties. White clouds are generally thought to be a fog of submicron ice particles similar to terrestrial cirrus clouds. White clouds are of all shapes and sizes, ranging from terminator haze lasting only a few hours to dense, 2000-km giants lasting days or weeks.

Yellow Clouds

Yellow clouds are those readily photographed in yellow or red light, but which are not seen in blue light. They may be small, dense, orange or yellow objects lasting only one or a few days, or they may start large and grow larger until they become a yellow veil covering most of Mars and lasting a month or

more. Yellow clouds are believed to be clouds of dust particles, perhaps 2-50 μ in diameter, raised by high surface winds.

4.1.2 DISCUSSION

Early Observations

Yellowish clouds and veils were reported by visual observers of Mars at least as early as 1809 (by Flaugergues), and white clouds were reported by Secchi in 1858 (Maggini, 1939). Such observations were made with refracting telescopes, color-corrected for visual observing. Under such conditions, color descriptions are quite subjective, but the differences in appearance which resulted in a distinction between yellow and white clouds were real enough.

In 1871, the dry photographic plate was developed, making astronomical photography a practical possibility rather than a stunt, as it had been during the wet plate era. The "natural" spectral sensitivity of a photographic emulsion extends from the ultraviolet to about 5200 Å, there being some dependence upon the exact ratio of halides used in the emulsion and the physical processing during manufacture. Although it was discovered by Vogel in 1873 that the range of spectral sensitivity could be extended with dyes, reasonably fast red plates were not commercially available until 1906 (Mees, 1954). Most early photography of Mars was done with "natural" blue plates exposed through a refracting telescope, color-corrected in the visual (yellow) region of the spectrum. The resulting blurred images were rather discouraging.

Lowell Observatory began an experimental Martian photographic program in 1901 with "encouraging" results (Lowell, 1905). Four plates taken in 1903 and 99 plates from 1905 of useful scientific quality still exist (Baum et al., 1967). In 1907, Lowell described their process of extending plate sensitivity to 6800 Å and the use of a filter to isolate the yellow-green region, for which their 24-inch refractor was color-corrected. Many excellent photographic images were obtained in 1907, largely with an 18-inch refractor taken to Chile, where Mars came much nearer to the zenith. Some of these photographs are reproduced in Slipher's 1962 book. Even more important was the development, for use in 1909, of filters for separately isolating blue and red light (Slipher, 1962). The blue images "surprisingly" showed no detail whatsoever.

The Violet Layer, Blue Clouds, and Blue Clearing

The Lowell Observatory's featureless, blue photographic plates of 1909 resulted in the belief of a "violet layer" or "blue haze" of sufficient opacity to make surface features undetectable, in the blue and violet wavelengths. Actually, most of the loss of contrast in the blue is an intrinsic property of the surface (see Sections 3.2 and 3.4). The question of a tenuous atmospheric layer cannot be dismissed so simply, however. Whereas surface detail normally becomes quite difficult to see at 4500 Å and below (McCord and Westphal, 1971; Slipher, 1962), at times, for periods usually lasting no more than a few days, surface detail becomes quite obvious at 4500 Å, and Slipher (1962) found good contrast even at 4250 Å during such periods. This is the so-called phenomenon of "blue clearing" discovered by Slipher (1937), the

name indicating belief that dissipation of an atmospheric layer was responsible for the improved visibility of surface features. A "clearing" may be hemisphere-wide, or more limited in extent, and occurs within a period of about one day.

Spacecraft observations have not yet contributed greatly to a solution of the "blue clearing" problem. Mariners 4, 6, and 7 all carried imaging systems with passbands too far to the red. The Mariner 6 and 7 ultraviolet spectrometer data suggest there is about three times as much Martian atmospheric scattering in the ultraviolet as would be expected from a pure molecular atmosphere (Barth and Hord, 1971). However, the thin haze layers detected at the Martian limb by Mariners 6 and 7 are whitish, not blue, and seem incapable of causing the contrast change attributed to the "blue haze" (Leovy et al., 1971).

Van Blerkom (1971) has carried out a series of calculations on the contrast changes that can be produced by forward scattering or isotropic scattering hazes of various optical depths. For values of optical depth and limb darkening which seem appropriate to Mars, as seen by Mariner 4 and given by Young (1969), it is possible to reduce contrast by means of isotropic scatterers at the sub-Earth point from 15 percent to 10-12 percent for varying sun angles. Forward scattering hazes are even less efficient in reducing contrast. An optical depth of 0.3 is required to reduce contrast to 2-3 percent, and this is some six times the value observed by Mariner 4. These observations alone may be sufficient to conclude that an aerosol layer is not responsible for the blue clearing phenomena, but Mars is a dynamic planet, and high quality photometry spread over some weeks or months is really needed to understand it.

Attempts have been made to correlate visual and photographic observations of blue clearings with areographic longitude, Martian season, and time from opposition. These results are given in Slipher (1962), but are not reproduced here because of considerable correlation of each with observational selection (ease of making the measurement). Some data on blue clearings are tabulated in Table 1.

If blue clearing does occur, and it is not (or not totally) an atmospheric effect, then some change in the surface itself must be responsible. The photometry of Boyce and Thompson (1971) suggests the intensity of the Martian bright areas is strongly phase dependent while that of the dark areas is not. Such a change in contrast with planetary phase and rotation could easily be responsible for many, if not all, of the "blue clearings." Pollack and Sagan (1967) have preferred to go the whole way and suggest there is no real clearing, the apparent clearing being due entirely to excellent seeing at times when the Martian atmosphere is cloud free, and when there is an area of intrinsic high contrast near the Martian central meridian. It is certainly true that a blue clearing cannot be detected unless there is a surface region of some contrast beneath. It is equally true that good seeing is required, since bad seeing can destroy visibility of all surface detail even in the red or infrared.

Table 1. Table of observations of Martian blue clearings.

Dates of clearing	Opposition date	Source
May 26-Jun 1, 1890	May 27, 1890	de Vaucouleurs, 1954
Nov 2-3, 1926	Nov 4, 1926	de Vaucouleurs, 1954
May 20-21, 1937	May 19, 1937	de Vaucouleurs, 1954
Jul 18-25, 1939	Jul 23, 1939	de Vaucouleurs, 1954
Oct 10, 1941	Oct 10, 1941	de Vaucouleurs, 1954
Nov 22, 1941	Oct 10, 1941	Slipher, 1962
Jun 13-14, 1954	Jun 24, 1954	Slipher, 1962
Jun 27-Jul 2, 1954	Jun 24, 1954	Pettit and Richardson, 1955
Aug 7 and 11, 1956	Sep 11, 1956	Slipher, 1962
Aug 23-Sep 3, 1956	Sep 11, 1956	de Vaucouleurs, 1957; Slipher, 1962
Oct 26, 1956	Sep 11, 1956	Slipher, 1962
Sep 3, 1958 ^b	Nov 17, 1958	Richardson and Roques, 1959
Oct 13-15, 1958	Nov 17, 1958	Slipher, 1962
Nov 6-10, 1958	Nov 17, 1958	Slipher, 1962
Nov 31, 1960; Jan 17 and 27, 1961 ^c	Dec 30, 1960	Smith, 1961
Sep 26-28, 1964; Oct 3-4, 1964; Dec 30, 1964-Jan 1, 1965; Mar 8-9, 1965 ^d	Mar 9, 1965	Capen, 1966
Mar 6, 1967; Jan 14, 1968 ^e	Apr 15, 1967	Capen, 1970

^aThis clearing occurred during the beginning of the great dust storm. Not all of the planet was covered during this period, and those dark areas visible in yellow light were almost equally visible in blue light.

^bNote that this clearing occurred 74 days before opposition, clearly indicating the apparent association with opposition to be an effect of observational selection.

^cA number of other dates showed lesser clearing than these three.

^dA number of other dates showed lesser clearing than these four groups.

^eModerate clearing was noted on 30 days between Dec 66 and Jan 68.

Nevertheless, there seem to be periods of excellent seeing, when surface detail is easily visible in the yellow and red, and when no hint of a surface feature can be seen in blue-violet light (Capen*).

Normal blue images of Mars, taken in good seeing, often have an irregularity, showing structure that is not correlated with surface features (Humason, 1961). Often bright areas on blue photographs correlate with white clouds seen visually. In other cases, white clouds are visible only as a thickening or brightening in the blue and violet images and are sometimes called blue or violet clouds. Dollfus (1961a) prefers to reserve the term "blue clouds" for clouds visible only in photographs using "deep blue filters" and located near the morning and evening limbs. Such blue clouds differ radically in polarization properties from white clouds and typically seem to be produced by $3\ \mu$ droplets (Dollfus, 1961a). Sometimes a blue image shows a distinct planet-wide banded structure (Slipher, 1962; Humason, 1961). In summary, blue images of Mars are far from being uniform and featureless at all times or from showing structure correlated only with surface features as would be anticipated for a pure, molecular atmosphere. At least there are certainly some atmospheric features of considerable opacity.

The observer of Mars "sees" the result of the combination of several phenomena occurring simultaneously. The reflectivity of the Martian surface decreases sharply from $6000\ \text{\AA}$ to $3500\ \text{\AA}$ (due possibly to the presence of ferric oxides), and contrast between light and dark areas is greatly reduced. Contrast between bright and dark areas may change with phase angle and angles of incidence and emission. Somewhere near $3000\ \text{\AA}$, the light scattered by atmospheric gas molecules becomes equal to that reflected from the surface, but molecular scattering decreases toward longer wavelengths according to the λ^{-4} Rayleigh law dependence. Added to these is light scattered from aerosols, which are certainly present in the Martian atmosphere, even though they may not constitute a violet layer or blue haze which can be dissipated, plus any changes in ground reflection. Even under conditions of perfect terrestrial seeing, or from a space probe, all surface detail except the polar caps and possible frost patches (which have a high constant reflectivity through the visible part of the spectrum) should disappear somewhere between $3000\ \text{\AA}$ and $4000\ \text{\AA}$ without any added atmospheric scattering.

"Explanation" of a phenomenon whose very existence is debated is always controversial. Dollfus and Focas (1966) find a photometrically determined surface pressure for Mars of 30 mb. The actual surface pressure is known to be about one-fifth of that amount. The difference, if not an instrumental artifact, must be caused by particulate scattering. Martian polarization, as measured by Gehrels and Teska (1962), is not consistent with pure Rayleigh scattering but might be compatible with atmospheric scattering by submicron particles and/or ground effects, in addition to some Rayleigh scattering. Kuiper (1964) has compared these results with theoretical scattering calculations for mixtures of variable size submicron ice particles with indefinite results. He notes that "pumping liquid nitrogen into an open vessel placed in very dry air" results in a blue cloud of submicron ice crystals (frozen by the evaporating nitrogen) having the sort of extinction properties required of the violet layer. When the air is not dry, a white cloud results.

*Private communication.

The most likely composition of particles in Mars' lower atmosphere would seem to be frozen H_2O or dust. Wilson (1958) compared a series of low dispersion (100 Å/mm) blue spectra taken during blue clearings with an identical set taken under normal conditions. He found periodic maxima and minima in the ratio of light reflected from Mars that were exactly supplementary to light transmitted through terrestrial noctilucent clouds. Noctilucent clouds are generally thought to be composed of submicron-size meteoritic dust or ice-coated particles of meteoritic dust. It is also interesting to note that the intensity of light, scattered from particles comparable in size to its wavelength, characteristically goes through a number of maxima and minima (Mie scattering). Furthermore, Leovy et al. (1971) have given reasonable arguments that the white "thin hazes" they observe can not be frozen CO_2 (although neither are they a violet layer). Above an elevation of about 20 km, frozen CO_2 is possible even in the equatorial regions, however, and CO_2 lies frozen on the ground in the pole caps, so CO_2 particles are certainly present on Mars.

In summary, there is good evidence for aerosols in the Martian atmosphere, and there seems to be fair (though not perfectly quantitative) evidence for occasional changes in the apparent contrast of Martian surface features in blue light. Spaceprobe evidence is insufficient because of the limited time Mariners 4, 6, and 7 spent near Mars and because quantitative photometry in the wavelength regions from 3000 Å to 4500 Å was not included in its investigations. It remains unclear whether there is any association between the aerosols and the apparent contrast changes.

White Clouds

Originally white clouds were defined as those which seemed white or bluish when seen visually. With the advent of filter photography, it became apparent that white and blue clouds were easily photographed at short visible wavelengths but disappeared in the red and infrared, a simple operational distinction. Differentiation between white and blue clouds is not so simple, nor is there general agreement that such a distinction exists, as both can be photographed in the blue. Dollfus' distinction, given on page 5, was based upon location and polarimetry. Polarimetry of dense white clouds suggests they are a fog of ice particles, similar to terrestrial cirrus clouds (Dollfus, 1961a).

Some white clouds are quite large, as much as 2000 km across, and remain visible for days or weeks. They may form or dissolve at their edges, may move at relatively high speeds, and have a tendency to appear above certain specific regions of the planet (Dollfus, 1961b). They may appear as bright prominences at the limb of Mars. Under excellent seeing conditions, large clouds may exhibit considerable fine structure. Large clouds also may be surrounded by an even larger area of thin haze, detectable only with a polarimeter. As previously noted, bands covering the full apparent diameter of Mars are sometimes visible on blue images of the planet.

Other white clouds are small, bright, and generally remain fixed in an isolated location (Dollfus, 1961b). These may be surrounded by a large, fainter cloud structure. The polar caps are usually said to be covered in Martian winter with a hood of clouds similar in character to these small bright clouds (see Section 4.2).

Clouds or hazes are often seen near the morning terminator of Mars but usually disappear in a few hours. Sometimes they are also seen to form near the evening terminator. Both morning and evening hazes are seen most frequently in the Martian spring (Dollfus, 1961b).

C. F. and V. W. Capen (1971) have considered the following morphological classes of clouds: polar hood, polar haze, planetary system cloud banding, limb brightening (nonrotating haze), diurnal cloud, recurrent cloud (diurnal orographic), seasonal cloud (stable topographic), and white area (frost or fog). This classification of clouds is primarily geometric, with only minor reference to possible causes or physical mechanisms, and at the current state of knowledge, it is more valuable than a speculative attempt at physical discrimination. Table 2 from C. F. and V. W. Capen (1971) is an indication of the fraction of observing nights on which the listed phenomena were observed somewhere on the planet during 1966-1968. Such a list is necessarily biased by the superior observations possible during the particular season (northern midsummer), when Mars was nearest Earth, and is hurt statistically by the single observing station, but it gains from uniformity, and does give some useful measure of just how common these phenomena may be.

Table 2. Martian clouds and hazes 1966-68
after C. F. and V. W. Capen (1971)

Classification	% observed of nights viewed
Arctic hood or haze (latitudes $+65^{\circ}$ to $+90^{\circ}$)	76.3
Northern hemisphere clouds and haze (latitudes 0° to $+65^{\circ}$)	98.0
Southern hemisphere clouds and haze (latitudes 0° to 90°)	63.5
Antarctic hood or haze (latitude -65° to -90°)	39.3
Morning cloud and haze	53.1
Afternoon cloud and haze	87.2
Cloud band	16.0
Recurrent cloud	35.5
Terminator projection	10.0
White area (frost/fog)	68.3

The famous "W" cloud of Mars seems to be a peculiar recurring white cloud. It was first observed and photographed by Slipher in 1907 and has been seen during several additional apparitions of Mars since then (Slipher, 1962). It was particularly prominent and received wide public notice in 1954. The W-shaped cloud always appears in the same place, the Tharsis region near Lacus Phoenicis, and "the main stems of the cloud pattern appear to coincide with the main (so-called) canals in the area" (Slipher, 1962). The "W" cloud was observed by Mariners 6 and 7 during the far encounter sequences (see Leovy et al., 1971; also 7F74 in Section 3.6). It must be noted that the cloud appears as a "W" in astronomical orientation. With north "at the top" it is an "M" cloud.

Although most "moving" clouds are of the yellow variety (see paragraphs following), some white clouds appear to show motion, both in the sense of growth and in apparent motion from day to day (Martin and Baum, 1969). This does not necessarily imply real motion. If the white clouds are the result of condensables, the apparent motion may only represent a propagating change in atmospheric conditions.

At least some white "clouds" are almost certainly made up of CO₂ and/or H₂O ice particles. The conditions and mechanisms by which such clouds, fogs, or frost can form are considered in some detail in Section 3.4. The composition and formation/dissolution of the polar caps are also discussed in Section 3.4. The polar hoods and their relationship to the polar caps are discussed in Section 4.2.

Yellow Clouds

Yellow clouds usually appear yellow or orange when observed visually. They are easily photographed in yellow or red light, but cannot be seen on blue photographs. Their disappearance in the blue may be caused by lack of contrast and by their being lower in the atmosphere than white and blue clouds, essentially the same reasons for the disappearance of surface detail in blue photographs. Even in red light, yellow clouds may be difficult to see because of the lack of contrast when above a Martian bright area, although when first forming they are often very bright. The existence of extended elements of a yellow cloud can sometimes be detected polarimetrically when they cannot be seen visually.

It is almost universally accepted at the present time that yellow clouds are dust clouds. *Polarimetric and thermal studies of the Martian surface indicate the virtually certain existence of finely divided material (see Section 3.1). The color of the clouds correlates with what would be expected for dispersed surface material. Polarimetric studies of the clouds themselves

*As final preparation was under way on this document, Mariner 9 was in orbit around Mars during the biggest "dust storm" ever observed on the planet. Early news releases from the Mariner 9 project seem to indicate that considerable evidence has been obtained confirming that yellow clouds are made up of airborne surface particulates (dust), but quantitative scientific data is not available at this writing.

do not disagree with the dust hypothesis (Dollfus, 1961a). Yet, this evidence is more circumstantial than direct, for example Perls (1971) offered an alternative carbon suboxide yellow cloud hypothesis.

Yellow clouds have a large range of sizes and shades of color. The most obvious are the great yellow "storms," which may grow in size until they nearly cover the planet. The great dust storm of 1956 began with local activity on August 20 (Earth date) and greatly intensified on August 28 with a "brilliant, orange-colored cloud" over Noachis, according to Slipher (1962). Kuiper (1957) first saw a group of "five or six bright yellow clouds" over Mare Sirenum on August 29. The differences in descriptions of the cloud development are probably due, at least in part, to the fact that Slipher was observing in Bloemfontein, South Africa, and Kuiper in west Texas; they were thus seeing somewhat different parts of the planet. However, both agree that by September 2, almost the entire planet was covered by a yellow veil which partially obscured most surface detail. Actually, a part of the surface was still unobscured as seen from Australia on September 3 (de Vaucouleurs, 1957). There were local areas of greater opacity which completely obscured the surface. This activity reached a maximum on September 7, according to Slipher (1962), and continued to some extent until at least September 22. A third description of the 1956 storm, the greatest ever observed on Mars until that of 1971, is given by Dollfus (1961b).

The yellow storm of 1971 first appeared, on photographs taken September 22, as a bright bar, some 2400 km long, lying across Hellespontus and Noachis in a northeast-southwest direction (Capen and Martin, 1971). There was no evidence of "activity" on photographs taken the previous day. During the succeeding 16 days, the westward moving front of the storm traveled completely around the planet to link with the more slowly expanding eastern front, at a longitude of about 240° (Capen and Martin, 1971). Figures 1 and 2 from the Planetary Research Center of Lowell Observatory show the day-to-day progress of the storm during this period. By the twentieth day, October 12, the entire planet was obscured, showing no surface detail on red images. After 60 days, the surface of Mars was still obscured, making the 1971 storm the greatest observed in duration, as well as area covered. Information on other major yellow storms is given in Table 3.

Small yellow clouds have been observed at most favorable apparitions of Mars, but they are not common. Some yellow clouds appear to move and have been followed for as long as 16 days (Gifford, 1964). In a study of old observations, Gifford (1964) found several yellow clouds which seemed to move with velocities in excess of 100 km/hr. The mean rate of advance of the 1971 storm appeared to be about 40 km/hr for a 16-day period (Capen and Martin, 1971). A detailed, uniform study of 95 discrete clouds of all types by the Planetary Research Center revealed 43 clouds which appeared to move (Martin and Baum, 1969). Thirty-five of these, those for which observations spanned more than 72 hours, showed a mean velocity of only 5.6 km/hr and a maximum velocity of 15 km/hr (Martin and Baum, 1969).

It is clear that the expansion of the cloud in a great storm could be caused by an expansion of the disturbance, as well as by motion of the actual cloud material. A small yellow cloud presumably cannot disappear too rapidly,



Fig. 1. 1971 Yellow storm, days 1-7 (September 22-28); contours overlaid on pre-storm map (Capen and Martin, 1971).



Fig. 2. 1971 Yellow storm, days 8-17 (September 29 - October 8); contours overlaid on pre-storm map (Capen and Martin, 1971).

Table 3. Table of major Martian "dust storms."

Date	Description	Source
September - December 1877	Schiaparelli observed vast clouds totally obscuring the "equatorial continent" between Syrtis Major and Ganges. On around the equatorial zone north of Mare Sirenum and Mare Cimmerium everything was veiled but not totally obscured.	Maggini (1939), p. 323-325
July 1909	A large part of the visible disk was covered by a yellow veil (grayish in some areas). Considered here to be pre-storm veiling.	Maggini (1939), p. 318-320
August 1909	Major yellow storm - nearly planet-wide - observed and sketched by Antoniadi (also by G. Fournier): By August 12, Mars had turned lemon yellow, where one could hardly distinguish markings normally as dark as Mare Tyrrhenum, Syrtis Major, and Sinus Sabaeus. Only Mare Sirenum maintained in August its usual intensity.	Antoniadi (1930), p. 40-41
August 15 - October 26, 1909	Major yellow storm seen on Lowell Obs. plates.	Capen and Martin (1972a)
September - November 1911	Major yellow storm seen on Lowell Obs. plates.	Capen and Martin (1972a)
November 3 - December 23, 1911	An orange yellow veil covered the entire region south of Syrtis Major and Sinus Sabaeus as far west as Thaumasia, and persisted for weeks. Also observed and sketched by Antoniadi.	Maggini (1939), p. 321-322 Antoniadi (1930), p. 41-42
August - mid October 1924	Major yellow storm seen on Lowell and Lick Obs. plates.	Capen and Martin (1972a)
Early December 1924 - mid February 1925	Major yellow storm observed and sketched by Antoniadi, and measured polarimetrically by Lyot. Polarization began to decrease about Dec. 1, and by mid-month surface detail was gone, hidden by a thick yellowish veil. Both came back to normal during February.	Antoniadi (1930), p. 42-43 de Vaucouleurs (1954), Plate VIII
August - November 1926	Major yellow storm seen on Lowell Obs. plates.	Capen and Martin (1972a)
Late May - July 1939	Total obscuration of the Utopia - Umbra region by a very persistent large yellow cloud. Late July, a general abnormal paleness of the disc was noted. Solis Lacus - Bosporos very pale.	de Vaucouleurs (1954), p. 88 (see ref. given)
August - September 1939	Questionable major storm. Little data on Lowell Obs. plates.	Capen and Martin (1972a)
November 12-28, 1941	A large cloud grew over Libya on Nov. 12 and began moving south. On Nov. 15 Slipper saw it as a vast system of several clouds more than 1000 km across. It was last seen over Phaethontis on Nov. 28. de Vaucouleurs describes it as yellowish or pinkish except on Nov. 13, when it appeared bluish-white.	de Vaucouleurs (1954), p. 339-341; Slipper (1962), p. 108-109
August - November 1941	Major yellow storm seen on Lowell Obs. plates.	Capen and Martin (1972a)
August 19 - September 22, 1956	Details are given in the main body of the text.	Slipher (1962); Kuiper (1957); de Vaucouleurs (1957)
August 19 - November 1956	Major yellow storm seen on Lowell Obs. plates.	Capen and Martin (1972a)
September - November 1958	Major yellow storm seen on Lowell Obs. plates.	Capen and Martin (1972a)
September 22, 1971 - January 1972	Major yellow storm - planet-wide. Details of developing stages are given in the main body of the text.	Capen and Martin (1972a, b) Capen and Martin (1971)
Refs: - Antoniadi, E.-M., 1930, La planète Mars, 1659-1929: Hermann et Cie., Paris, 239 p. - Capen, C. F. and Martin, L. J., 1972a, Photographic survey of Martian yellow storms: to be published. (Abstract in Bull. Am. Astronom. Soc., v. 4, no. 3, pt. II) - Capen, C. F. and Martin, L. J., 1972b, Mars' great storm of 1971: to appear in Sky and Telescope, v. 43, no. 5, May.		

however, as some time is required for the particles to settle out of the atmosphere. Therefore, apparent motion of such a discrete object is likely to be real motion. Martin and Baum (1969) suggest the high apparent velocities noted by Gifford (1964) may be caused by errors in the original observations reported in the old literature. There is no obvious objective way to handle such nonphotographic data.

The Planetary Research Center work indicated that clouds generally tend to avoid the darker areas on Mars and are particularly prevalent in the zone from 20°N latitude to the equator (Martin and Baum, 1969). These workers also found the majority of clouds to move east and west, especially to the east, rather than to the north or south. Their charts and those of others show a strong preference for cloud activity in certain discrete geographic locations. Capen and Martin (1971) note the strong preference for the formation of great yellow clouds in the Hellas-Noachis region (1909, 1911, 1924, 1939, 1956, and 1971), for example.

It is difficult to believe that volcanic activity or meteoritic impacts could be responsible for the great yellow storms of 1956 and 1971. Therefore, it is generally assumed that the dust particles are raised by suitably high winds. (It must be recognized that more than one mechanism actually could be active.) Very high wind velocities are required to initiate movement of particles of any size, large particles (~1/2 mm) being easier for wind to move than small ones (Ryan, 1964). Even particles of optimum size require near-surface winds (at 2-m elevation) of 450-500 km hr⁻¹ to move them in a 5-mb atmosphere (Ryan, 1969).

Neubauer (1966) showed that large dust-devils offered an attractive mechanism for moving dust aloft. Extensive studies by Ryan (1969) indicated that velocities adequate to entrain dust should be available in the form of "vortex systems of the dust devil type." These systems originate in a shallow, superadiabatic layer near the surface. Conditions on Mars are such that they should originate rather more frequently and with greater diameter (and lifting ability) than on Earth (Ryan, 1969). Once large particles begin to move, they collide with small particles, knocking them into the air. Dust-devils have a good upward component of velocity (Neubauer, 1966). Larger-scale winds may also have a vertical component, perhaps as great as 6 m sec⁻¹ (Gierasch and Goody, 1968). There is good reason to believe that dust can be raised from the surface, at least to the tropopause, to form yellow clouds.

The altitudes of yellow clouds have often been estimated, but the results vary wildly. They are "mostly low level objects, lying generally between 3 and 5 miles above the surface," according to de Vaucouleurs (1954). Slipher (1962) states that "most of the examples best observed and most susceptible of accurate measurement have been found at heights of 18 to 20 miles." Altitude "measurements" have generally been made on terminator clouds (clouds that remain illuminated on the dark side of the terminator because of their height above the ground) by assuming the apparent horizontal distance between cloud and terminator is a direct function of altitude. However, statistical errors are quite large for the small angles involved (≤ 0.1), and there are numerous possibilities for systematic error in such measurements.

Small yellow clouds usually last for no more than two to four days. The particles involved must be at least 1-2 μ in diameter (larger than the wavelengths of yellow and red light in which they are easily photographed). They very probably never rise higher than the tropopause. In fact, particles must be at least 20 μ in diameter and rise no more than ~5 km, if they are to settle out of the atmosphere in four days. Therefore, yellow clouds must include many particles 20-50 μ in diameter. The yellow veils lasting a month or more can easily be accounted for by including smaller particles or by maintaining the lifting mechanism.

In summary, it is certainly possible, based upon all direct and indirect observational evidence, that the yellow clouds are dust clouds. It is, in fact, probable that the yellow clouds are dust clouds, but proof of this theory must await the detailed evidence from Mariner 9 or future studies.

Gray Clouds and Bright Spots

As is quite obvious, Martian meteorological knowledge is largely qualitative, and at times geological changes in the surface even may be confused with atmospheric phenomena. Identical events may be described quite differently by different observers or differing events described similarly. It is this lack of precision that makes it difficult to evaluate reports of potentially great importance, such as those that follow. These reports are a few among many.

Ley (1963) has summarized reports of strange dark-gray clouds, made by several of the best known Japanese observers of Mars. Four of these clouds were seen during 1950 and 1952, in an area about 500 mi across, extending from Mare Sirenum across Electris to Eridania. White clouds often appear somewhat gray, but the experienced Japanese observers felt those reported were unique both in color and in the great height to which they appeared to rise. They have chosen to attribute the gray clouds to volcanic activity. Such a hypothesis is possible, of course, but can hardly be supported from the observations alone.

Over the years, there have been a number of reports of bright spots or flares on Mars, typically lasting five or ten minutes. Some of these reports have been made by reputable, experienced observers. At least two Martian sites have reportedly exhibited repeated flares, again resulting in hypotheses of volcanic activity. A brief list of flare observations and characteristics is given in Table 4. Whether these flares are truly the result of volcanic activity, even if volcanos exist, or whether they might be specular reflection from a temporary patch of surface ice or some other surface phenomena, is pure speculation.

Table 4. Table of bright flares and spots observed on Mars
(from Katterfeld, 1966).

Date	Observer	Instrument and Observatory	Location of flare or spot	Characteristics and duration
Jun 4, 1937	Sitzuo Mayeda	8-in. reflector	Close to Sithonius Lacus; +55° lat., 240° long.	Considerably brighter than the polar cap and the white clouds. Flickered like a star, and after 5 min it was hidden from view (possibly due to rotation of the planet). (See Saheki, 1955.)
Dec 8, 1951	Tsuneo Saheki	8-in. reflector, planetarium at Osaka, Japan	Western portion of equatorial Tithonius Lacus	Brighter than the north polar cap. Flickering light and stellar brightness of the 6th magnitude for 5 min. It then began to be extinguished and changed into a grayish cloud having a diameter of more than 300 km. The entire phenomenon lasted about 40 min. (See Saheki, 1955.)
Jul 1, 1954	Tsuneo Saheki	8-in. reflector, planetarium at Osaka, Japan	Edom Promontorium (at the equator)	In 10 sec the color changed from a whitish-yellow to a bright, pure white, and then changed to yellowish-white. Duration of the flare was 5 sec. (See Saheki, 1955.)
Jul 24, 1954	Clark McClelland	13-in. refractor, Allegheny Obs. of Pittsburgh University, Penn.	Edom Promontorium	Flare was visible for about 58 sec. In the opinion of the observer, it was caused by a volcanic eruption.
Nov 5, 1958	Sadao Murayama	20-cm refractor, National Science Museum in Tokyo, Japan	South of Tanais Plateau, southwestern edge of Aphrodite Mare (Acidalia); +35° lat., 42° long.	Small but very bright spot, white in color. Lasted about 5 min. From Jul 23 to Aug 3, 1954, a similar white spot was observed at the same location by Tsuneo Saheki in the form of a very bright, small cloud.
Nov 6, 1958	Sigeji Tanabe	8-cm reflector, Sitsuoike, Japan	Southern edge of Tithonius Lacus	Brightness same as for the polar cap for 4 min.
Nov 10, 1958	Sanenobu Fukui	25-cm reflector, Kobe, Japan	Northeastern part of Solis Lacus	Brightness same as for the polar cap for 5 min. Diameter of spot (according to a figure) about 250 km.
Nov 21, 1958	Tsuneo Saheki	—	Northern edge of Hellas and Edom Promontorium	Two bright spots. Visibility below 5 according to the standard scale.
Nov 21, 1958	Itsiro Tasaka	32.5-cm reflector, Wakayama, Japan	Northern edge of Hellas and Edom Promontorium	The same spots as above, but visibility 6+7. Yellowish-white cloud over northern part of Hellas. Both flares lasted about 5 min, together with phases of increase and decrease in brightness--15 min. After several minutes, the flares reappeared.

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4.2 SEASONAL ACTIVITY

DATA SUMMARY

The Polar Caps and Hoods

The Martian polar caps appear to be deposits of some solid substance, most probably CO_2 (and small amounts of H_2O), condensing during the fall and winter in each hemisphere and then subliming during the spring and summer. The polar hoods are white clouds which hide the polar regions when photographed in blue or violet light during the fall and winter. Typical time behavior of these features is shown below. Lines indicate typical periods when these features are visible. Lengths of seasons are given in Earth days. (The symbols L_S and η are defined in the Appendix.)

	$(\eta=85^\circ)$ $L_S=0^\circ$ Vernal* Equinox	$(\eta=175^\circ)$ $L_S=90^\circ$ Summer* Solstice	$(\eta=265^\circ)$ $L_S=180^\circ$ Autumnal* Equinox	$(\eta=355^\circ)$ $L_S=270^\circ$ Winter* Solstice	$(\eta=85^\circ)$ $L_S=360^\circ$ or 0° Vernal* Equinox
	Spring	Summer	Fall	Winter	
Northern Hemisphere					Cap Hood
Length	199 days	183 days	147 days	158 days	
Southern Hemisphere					Hood Cap
	Fall	Winter	Spring	Summer	

Seasonal Behavior of Clouds and Whitenings

See Figs. 8 through 10.

The Wave of Darkening

The wave of darkening is "a progressive albedo decline of the Martian dark areas starting in local springtime from the edge of the vaporizing polar ice cap and moving towards and across the equator" (Sagan and Haughey, 1966). Its reality as a wave recently has been seriously questioned.

*Strictly for the Northern Hemisphere. Adoption of the same convention for designating the equinoctial and solstitial orbital points as used for Earth in astronomy.

Seasonal Behavior of Surface Features

Besides intensity (albedo) changes, dark areas show change in color, shape, size, and internal appearance, while light areas also change in color and structure. These changes are best shown in detailed descriptions of the changes occurring in individual areas (Tables 4-7) and in a series of color maps (Figs. 8-10).

INTRODUCTION

The first known drawings of Mars showing features which can definitely be identified are Christiaan Huygens' maps of November 28, 1659, clearly showing Syrtis Major, and of August 13, 1672, showing the south polar cap (Ley, 1963). J. D. Cassini saw both caps in 1666. The first astronomer to realize that both the polar "white spots" and the equatorial dark areas changed in appearance from opposition to opposition was Giacomo Filippo Maraldi, who observed every opposition of Mars from 1672 until at least 1719 (Ley, 1963). For more than 250 years, then, it has been realized that Mars is a changing world, and famous planetary astronomers such as Herschel, Schroeter, Beer and Von Mädler, Secchi, Lockyer, Kaiser, Dawes, and Proctor studied this planet, which appeared more Earthlike than any other. The modern period of good maps and really useful records of surface changes began with Schiaparelli's work during the excellent opposition of 1877.

Mars undergoes many sorts of change. There are the apparent changes as seen from Earth caused by the rotations of Mars and Earth and by the tremendous variation in the distance separating the two planets. Because the axes of Earth and Mars point in different directions, the sub-Earth point on Mars changes through almost 50° of areographic latitude, causing a great change in perspective. During this time there are also more subtle changes in appearance caused by changes in the photometric coordinate (see Section 3.2). There are changes caused by the appearance and disappearance of various meteorological phenomena such as are discussed in Section 4.1. Some of these phenomena are not completely random, but appear to be somewhat a function of season. Changes in polar caps and in the appearance and photometric properties of Martian dark areas are obvious seasonal changes and the primary subject of this section.

Since 1969, the many changes occurring on Mars, both in its atmosphere and on its surface, are monitored photographically, approximately hourly, through each apparition, by an International Planetary Patrol (IPP) network of observatories distributed around the world. Each patrol station is furnished with identical 35-mm cameras and filters (red, green, and blue), and returns its (fourteen-exposures) filmstrips to the coordinating Planetary Research Center at Lowell Observatory for development, editing, mounting, cataloguing, copying, etc. An almost continuous and homogeneous coverage of the planet during its apparition has thus become available. This data permits detailed studies of the various seasonal and secular changes on Mars. Many thousands of photographs of Mars have already been obtained under this program, more than doubling the pre-program Lowell Observatory collection. A description of this program has been given by Baum et al. (1970).

The rare flyby missions, such as Mariner 1964 and Mariner 1969, obviously cannot monitor the planet's complex seasonal evolution in just a few days period. They can only photograph the planet at a particular seasonal time. The encounter time of Mariner 1969 with Mars took place during its Northern Hemisphere's early autumn, and Southern Hemisphere's early spring ($L_S \approx 200^\circ$).

Orbital missions, on the other hand, such as Mariner 1971, are designed to make a detailed investigation and lengthy surveillance of the planet's fixed and variable features and study time-varying phenomena of both the surface and atmosphere. Specific variable phenomena to be studied closely by Mariner 9 include: (1) wave of darkening, (2) polar caps phenomena, (3) non-polar white clouds and whitenings, (4) yellow clouds and dust storms, and (5) hazes (for a description of the Mariner 1971 TV Experiment, see Mazursky et al., 1970). The seasonal activity is to be studied over a (terrestrial) year or more, depending upon the spacecraft operating lifetime. It is hoped, therefore, that at least half a Martian year of seasonal activity will be recorded by its TV cameras and other instruments.

POLAR CAPS AND HOODS

Polar Caps

The first recognition (in 1784) that the variation in the "white polar spots" of Mars is seasonal, and the suggestion that the spots are true polar caps of snow and ice, were due to William Herschel (Ley, 1963; Slipher, 1962). Measurements of the waxing and waning of the caps, begun by Herschel, have shown little change over a period approaching 200 years. Figure 1, compiled by Slipher (1962), shows the regression of the south cap as observed through many seasons.

There is considerable difference in the north and south polar caps of Mars caused by the asymmetry in Martian seasons. The south cap is formed during the long, 382 (terrestrial) days of southern fall and winter when Mars is near aphelion, and it covers more than 70 areocentric degrees at greatest extent (extending below latitude -55°). The north cap is formed during the short, warmer 305 (terrestrial) days of northern fall and winter when Mars is near perihelion, and it usually measures only about 53° at maximum extent (Slipher, 1962).

Quantitative photometric and polarimetric data on the seasonal evolution of both polar caps and hoods have been given by Focas (1961 and 1962). See Fig. 2.

The polar caps (and hoods) of Mars are difficult to observe at the telescope from Earth because they are viewed from the side, with highly oblique viewing angles, especially near the poles. Because of the orbital geometry and inclination of the rotational axis with respect to Earth, it is presently the larger springtime South Cap which is closer and more favorably tilted for viewing during perihelic oppositions, while the smaller springtime

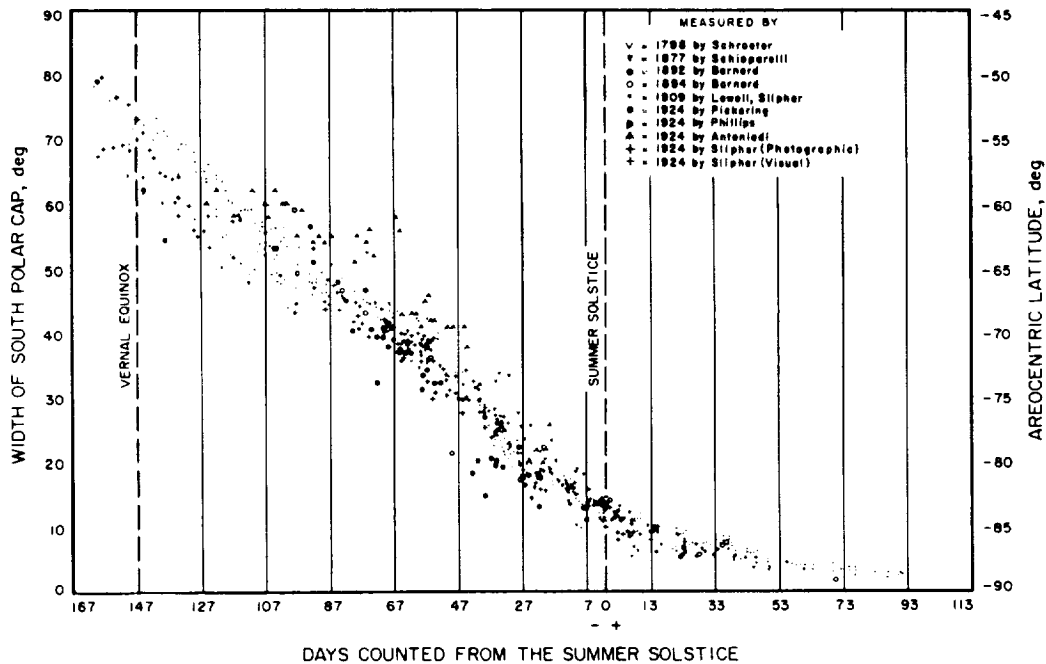


Fig. 1. Measured width of the south polar cap of Mars for various oppositions from 1798 to 1924. This figure embraces the Martian season from before the vernal equinox to 94 days after the summer solstice. Other measures derived from drawings in 1781, 1783, 1815, 1830, 1845, and 1862 were checked with those shown here, but no notable deviations were found other than accidental errors attributable to optical limits of the observer's telescope. The plotted measures shown in the figure agree very well indeed, and the deviations in the measures by the same observer are of about the same order as those that occur between different observers. This study revealed no evidence of any irregularity in the melting of the south cap at any of these oppositions during this long period of observation. (Slipher, 1962)

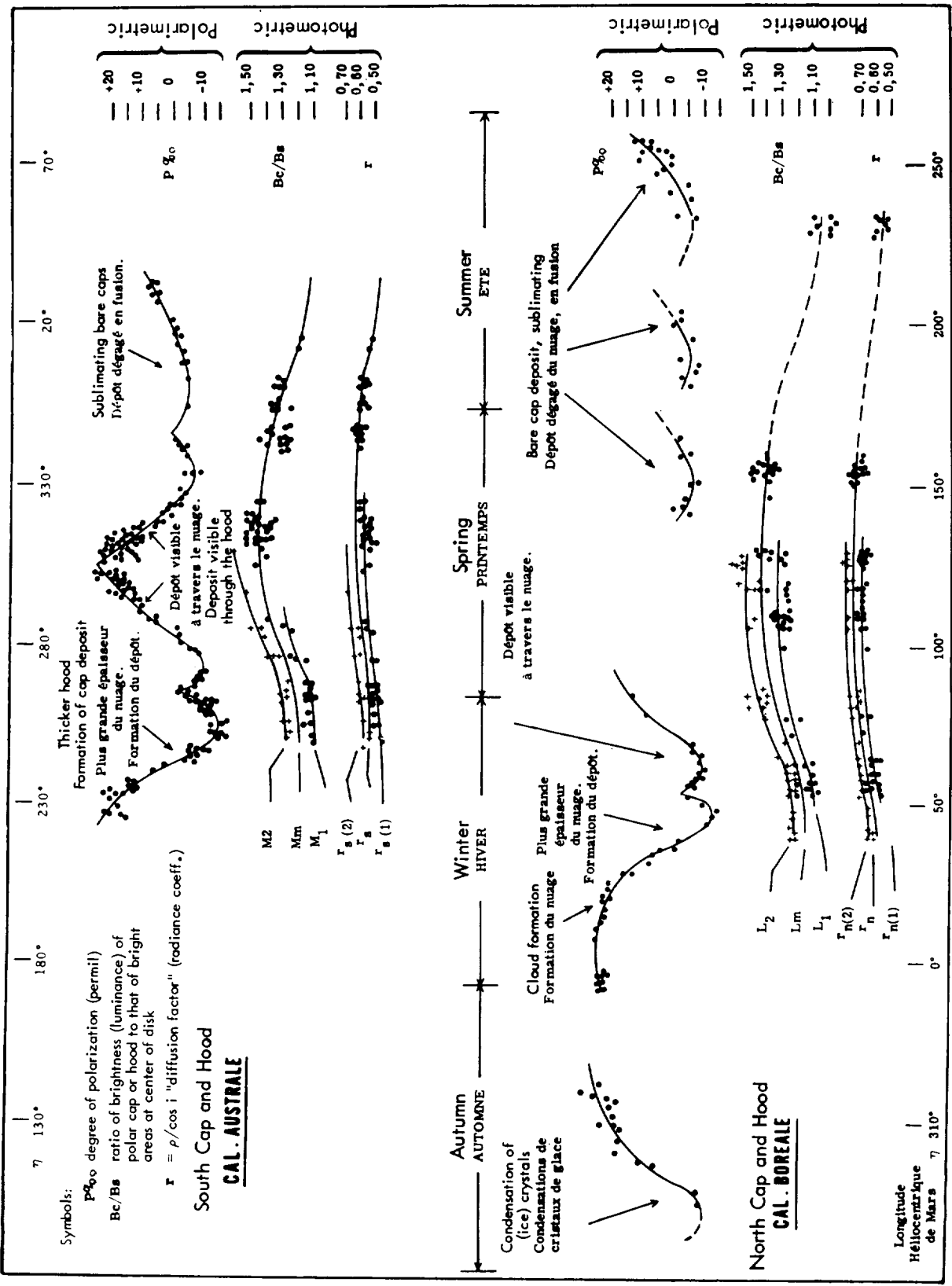


Fig. 2. Seasonal evolution of the Martian polar caps and hoods according to polarimetric (top) and photometric (bottom) measurements (Focas, 1961).

North Cap is best seen during aphelic oppositions. Thus, understandably, more observations have been made of the South Cap in the past (see the literature from Schiaparelli to de Vaucouleurs). Some observers (for example C. Capen), however, have specialized in the North Cap, which is more difficult to study. There is a compensation, however, for observers situated in our Northern Hemisphere, for at aphelic opposition times Mars is then at much higher declination, usually resulting in better seeing and longer observing periods.

Polar Hoods

During the fall and winter in either hemisphere of Mars, the polar areas are covered by a very large hood of clouds, often somewhat dull bluish-white in color and with an irregular diffuse edge. The early fall north polar hood was photographed by Mariners 6 and 7 in the FE series (see Section 3.6). The clouds usually appear large and bright in violet and blue photographs, although varying considerably in extent from day to day. Yellow and red pictures may show a much smaller bright region, where perhaps the forming cap is visible through the hood, or they may show almost nothing. Sometimes in late fall-early winter the hood becomes tenuous in places or may pull back partially, apparently revealing a portion of the deposited cap. By mid-winter the hood appears to be very thick and stable. Around vernal equinox (spring) time, the polar hood breaks up and finally dissipates, unveiling the much smaller true polar cap which is brilliant white and sharp. (The cap appears sharp in red light and brilliant in green and blue light.) Throughout spring (and summer) the cap remains well-defined, appearing practically constant in size from night to night, but very gradually regressing. A beautiful series of photographs illustrating these points has been published by Slipher (1962).

The southern polar hood reaches, in average, a latitude of -40° , spanning then an equivalent breadth of 100° areocentric. Its outline and seasonal behavior are quite irregular. The northern hood is not as large, but is definitely more regular. Usually extending down to slightly below $+60^\circ$ (equivalent breadth 60° areocentric), it may reach $+50^\circ$ latitude as in 1967 (Capen and Capen, 1971, 1972), or even exceptionally lower to $+40^\circ$ as in 1960 (Slipher, 1962).

Photometric and polarimetric data on the seasonal evolution of the polar hoods are shown in Fig. 2.

The Dark Polar Fringe*

The so-called dark polar fringe, also known as the polar band, or collar, surrounding the retreating polar caps, is said to have been seen first by Beer and Von Mädler as early as 1830 (Slipher, 1962). The fringe is not seen at the telescope when a polar cap is at its maximum extent nor is one visible during the slow, final demise of a cap (de Vaucouleurs, 1954). During the time of retreat, however, a zone most often described as 'bluish' develops contiguous to the cap, reaching its greatest width at the time of maximum rate of vaporization (de Vaucouleurs, 1954).

*Recently, Pang & Hord (Icarus, Dec. 1971) interpreted the collar as a photometric effect due to oblique viewing of glazed CO_2 -ice layers bared by the retreating cap.

The dark fringe appears to many observers to be more than just an effect of contrast between the brilliant cap and its relatively dull surroundings. Quantitative studies by de Vaucouleurs and by Dollfus identified a contrast effect, yet seemed to confirm the reality of the fringe (de Vaucouleurs, 1954). The behavior of the fringe may be identical to that of other areas of the planet that take part in the wave of darkening.

The dark fringe has sometimes been called the melt zone, implying it to be an area where liquid water exists for a brief time, wetting the ground before evaporating. This is most unlikely since sublimation of surface ice will occur rather than melting on Mars, as shown by Ingersoll(1970). Furthermore, theoretical polar temperatures will not exceed 0° C.

The existence of the dark fringe has been held in doubt, especially in recent years, by a number of theoreticians who consider it to be just another optical-physiological illusion (a contrast effect) produced in our ground-based telescopic observations. The Mariner 7 flyby over the South Polar Cap could not resolve this controversial question, since the flyby took place too early in Southern Spring. The polar dark fringe was first seen two months later at the telescope (late September 1969). The black border appearing in the NE Mariner 7 pictures around the brilliant South Cap is only the product of the TV camera system's "automatic gain control" used to obtain "maximum discriminability" versions of the pictures, and does not appear in the photometric versions (see Section 3.6, Photographic Atlas). Thus, the polar dark fringe is still a questionable Martian phenomenon.

Boundaries of North and South Polar Caps

Fischbacher, Martin, and Baum (1969) made a statistical study of the boundaries of both caps during their regressional phase on more than 3,000 photographs (yellow and red), obtained between 1905 and 1965. Measurements of boundary latitude at each of 36 meridians, separated by 10° in areographic longitude, were determined by superposition of the appropriate coordinate grid or graticule on each photograph. The Martian year was divided into 36 "seasonal" intervals, each spanning 10° in areocentric longitude of the Sun (LS). The mean latitude (combining all apparitions 1905-1965) at each selected meridian and for each 10° seasonal interval was calculated by computer, and the results tabulated. Figures 3 and 4 are the final diagrams showing the successive mean boundaries for each regressing cap.

Conclusions from this statistical study are as follows:

The South Cap recedes more regularly than the North Cap. During the entire southern spring (LS: $180-270^{\circ}$), the South Cap boundary was found to be "unusually well-defined and exceedingly repeatable in its behavior from one Martian year to another." Only small but significant differences were detected for individual meridians. Comparison of the 36 meridian curves with the average curve for all meridians, again showed a more regular behavior for the South Cap.

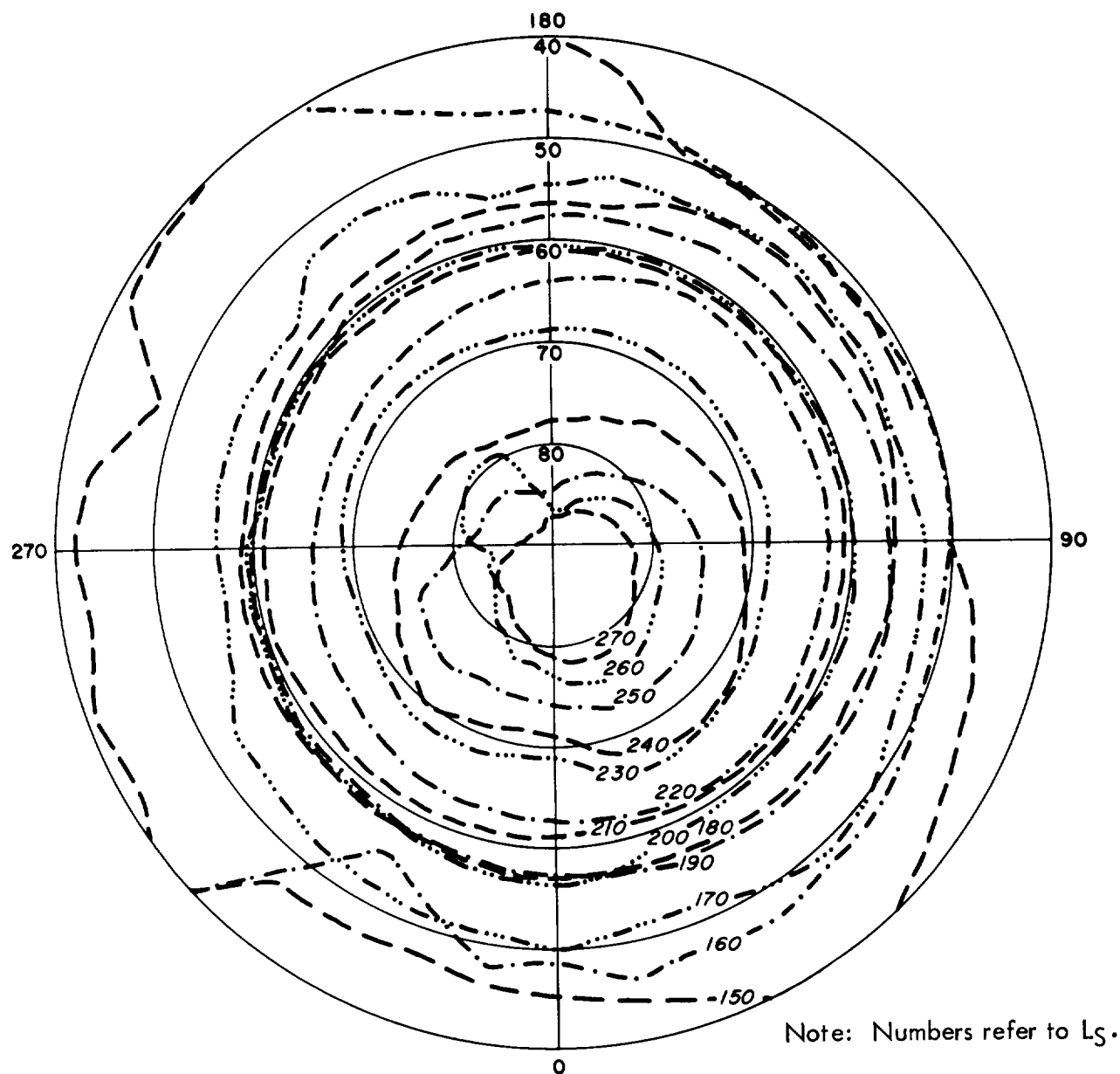


Fig. 3. Seasonal boundaries of the South Polar Cap as viewed from the south (Fischbacher et al., 1969).

Although the two caps differ substantially in their spring-summer decay patterns, each cap follows a rather well-defined curve, repeatable from year-to-year. However, there are slight variations from year to year, as will be seen later, especially for the North Cap.

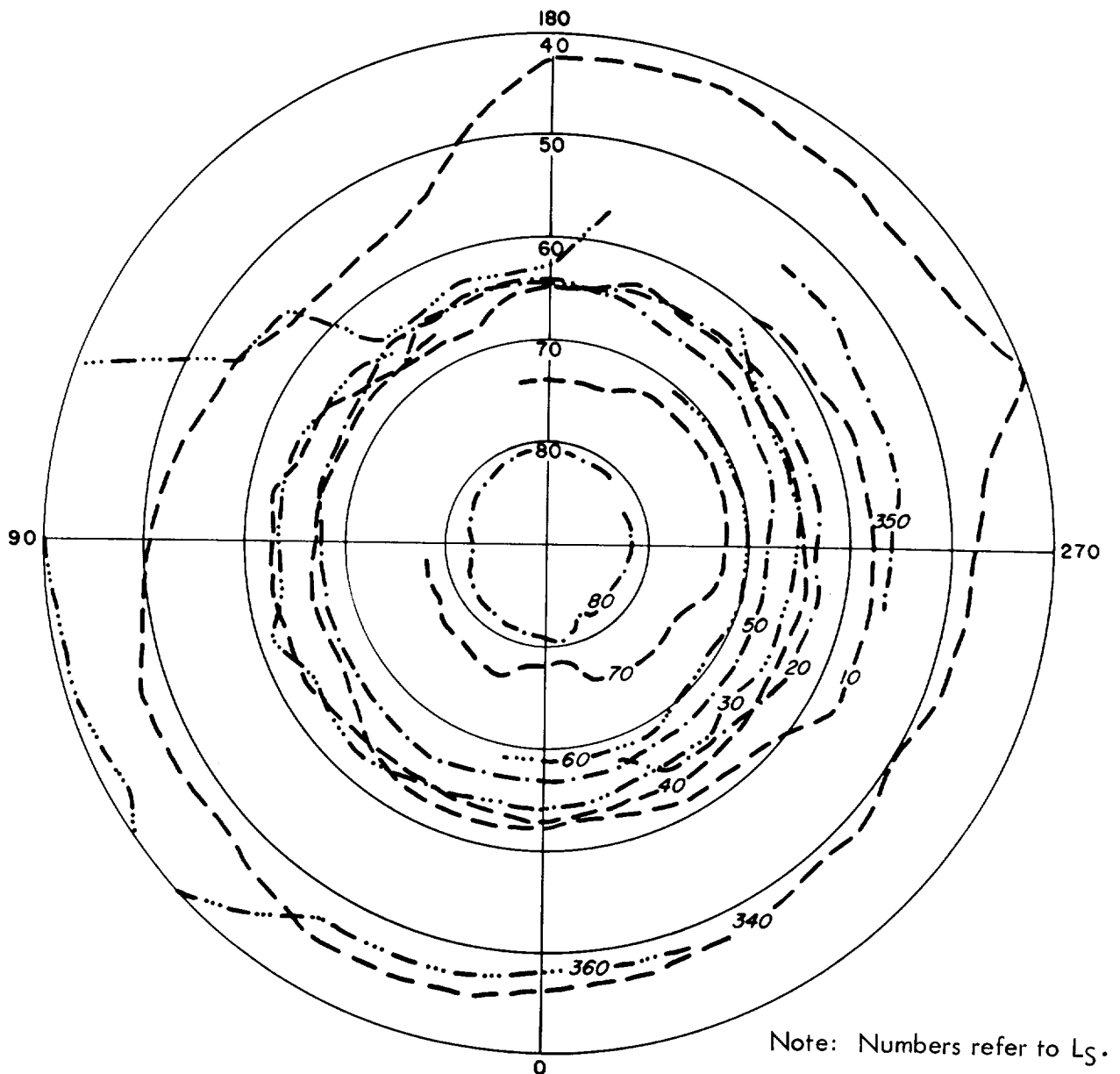


Fig. 4. Seasonal boundaries of the North Polar Cap as viewed from the north (Fischbacher et al., 1969).

South Cap Regression

The regular regression of the South Cap is illustrated schematically by the regression curves of Antoniadi (1930), Slipher (1962, Fig. 1) and Fischbacher et al. (1969; Fig. 5) which are essentially in good agreement.

The disintegration of the sublimating South Cap is well documented historically up to modern times and follows the familiar pattern described in the following: In early southern spring ($L_S = 200-215^\circ$) the fully expanded South Cap

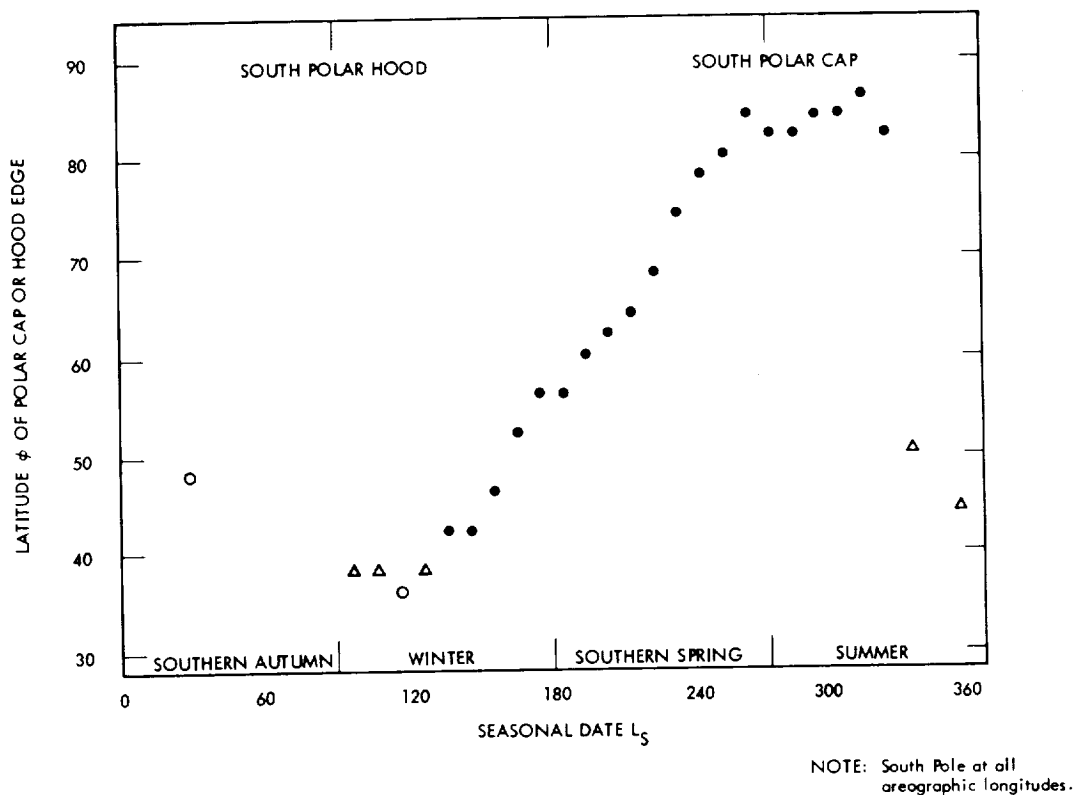


Fig. 5. Regression curve of the South Polar Hood and Cap, mean 1905-1965 (Fischbacher et al., 1969).

spans about 60° areocentric, and begins slowly shrinking. By late spring ($L_s = 240^\circ$) its diameter has decreased to about 40° and its regression rate has started to speed up considerably. Rifts or dark fissures (called Rima, Depressio, Fretum, ...) begin to make their appearance, signaling the rapid breakup phase of the cap, with gradual isolation of large bright promontories or islands (called Mons) along its edge. Thus, the bright Thyles Mons appears south of Phaethontis, separated from the main cap body by the often large Depressio Parva (at longitude 150° - 210° W) and the bright double-lobed Argenteus Mons, south of Argyre I, separated by the narrow rift Rima Angusta (at 30° - 50° W). The large bright Novus Mons, otherwise known as the "Mountains of Mitchel," covering the underlying surface feature Novissima Thyle, becomes well separated by the large Rima Australis (at 300° - 340° W). Later, by early Summer ($L_s = 280^\circ$), this Novus Mons becomes completely detached from the main cap by both Depressio Magna extending eastward the enlarged Rima Australis, and Rima Brevis. By then, the cap is going through its most rapid regressional phase; the rifts are very dark, and the promontories and islands have become very brilliant. (In 1971, de Vaucouleurs found Novus Mons to be "almost sparkling.") The controversial "dark polar fringe" is then best seen at the telescope. Other rifts are also formed; in particular, Ulyxis Fretum and Rima Brevis which separate bright Thyles Collis, south of Thyle II (at 220° - 270° W), on two sides.

Around the disintegrating irregular cap, there are a number of darkened areas: *Depressio Hellespontica* (near longitude 330° W), *Promethei Sinus* (near 260° W), *Noti Sinus* (near 200° W), *Palinuri Fretum* (near 150° W), *Tiphys Fretum* (near 220° W), and *Depressiones Aoniae* (near 120° W). All these areas, as well as the rifts and promontories or islands mentioned, are easily located on de Vaucouleurs MM'71 Planning Charts of the South Polar Regions (see Fig. 6), where both mid-spring and mid-summer aspects of the cap are represented. When mid-summer comes ($LS = 320^\circ$), only a roughly triangular remnant cap, *Hypernotius Mons*, of about 7° maximum extent is left. According to de Vaucouleurs (1972): "notwithstanding the frequent published statements to the contrary, the residual polar cap never evaporates completely before haze (hood) begins to form over the south polar regions at the end of summer." The mean position of the centroid of the small eccentric residual cap is at 23° W, 84.7° S (de Vaucouleurs 1972, from a dozen best determinations at 1877 to 1941 perihelic oppositions).

North Cap Regression

A mean regression curve (period 1905-1965) for the somewhat irregular North Cap was issued by Fischbacher et al. 1969 (see Fig. 7). This curve, it should be noted, is not in agreement with the classical curve given previously by Antoniadi (1930) covering mostly an earlier period (1856-1929). It is to be considered more reliable than Antoniadi's.

Regression curves for the North Cap were obtained by Capen and Capen (1970, 1972) for the four successive apparitions in the period 1962-1969, when it was advantageously tilted towards Earth. See Figs. 12 through 15. These curves, which are in fair agreement with Fischbacher's mean curve, show a generally similar overall behavior in the retreat, but with irregularities.

The general evolution, as depicted by Capen and Capen (1970, 1972, is as follows: a slow regression in the first part of spring (1° per 10-20 days when $LS = 0-45^\circ$), followed by a rapid regression in the second part of spring ($LS = 45^\circ-90^\circ$), with a temporary halt in late spring (caused by arctic hazes), resumption to maximum rate near summer solstice (1° per 3 days), then considerable slowdown by mid-summer (1° per 20-30 days when $LS \sim 135^\circ$), and finally a virtually static cap by late summer ($LS \sim 160^\circ$) with a remnant diameter of about 6° . The evolution of the late 1967 cap was abnormal: no halt in late spring, slower rate around solstice and in early summer, finally a large remnant cap of 10° . Evidently, the arctic climate was colder than normal in 1967. Table 1 compares the rates at various seasonal times for the four apparitions. The halt in the retreat takes place when Mars is close to aphelion passage ($\eta = 155^\circ$, or $LS = 70^\circ$). It lasts only a few days, but the North Cap may even increase in diameter by 1 or 2° , as was observed in 1963 and also in 1960 (Miyamoto and Hattori, 1968). The usual remnant cap of 6° diameter agrees with the average given by Slipher (1962). The centroid of the residual cap is only about 1° away from the North Pole.

The areal pattern displayed by the regressing North Cap is repeatable in normal years. The rapidly disintegrating summer cap (near maximum rate) produces three prominent white areas at the same locations, which linger around the main cap edge as bright projections, varying in size and brightness, and eventually become detached as islands, as the cap further retreats to less

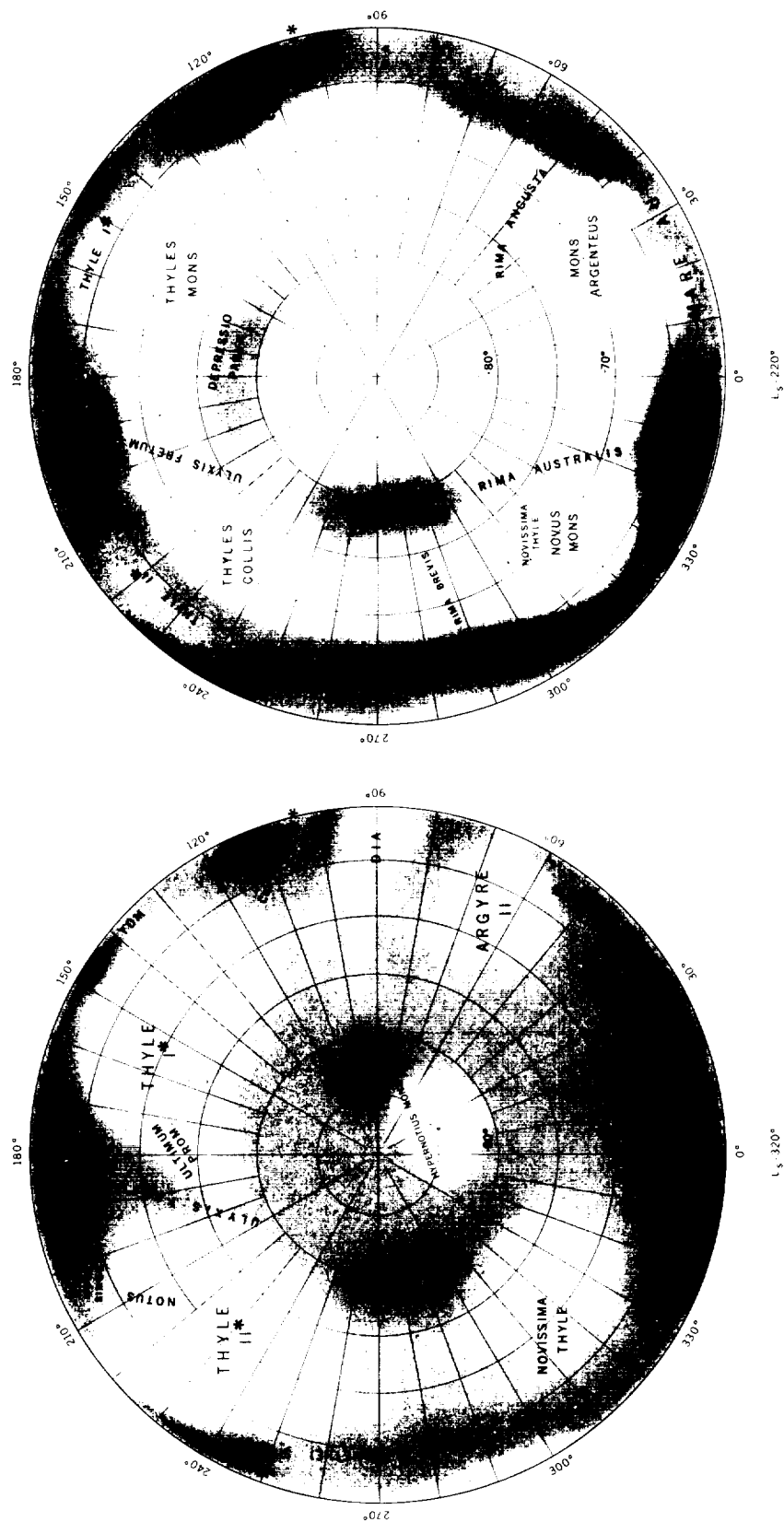
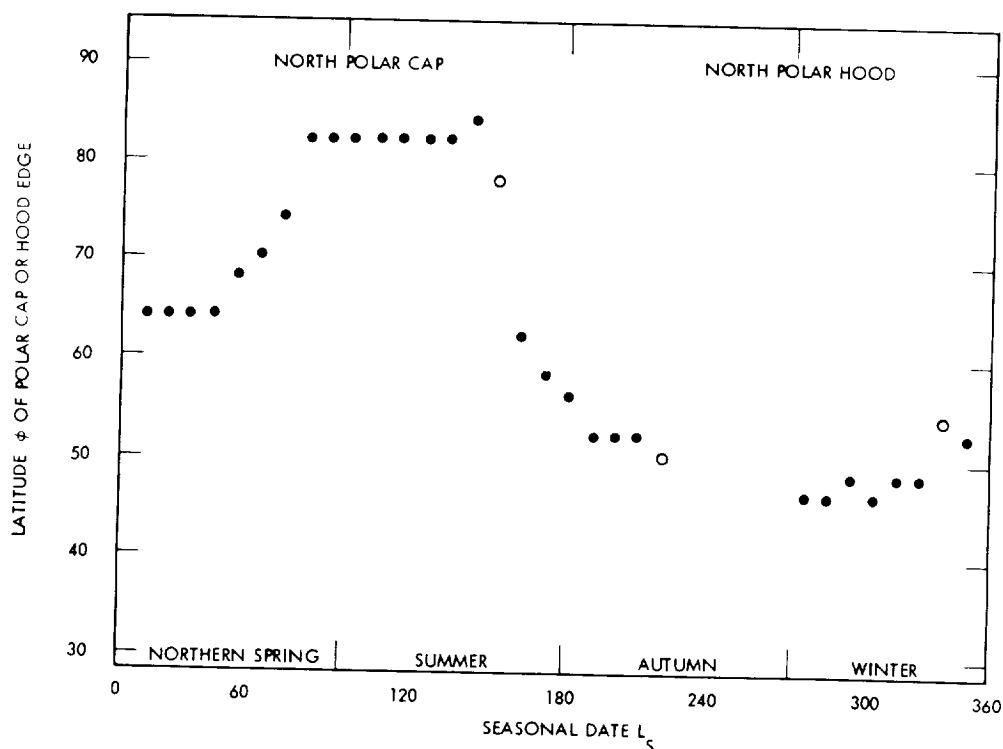


Fig. 8. Mariner Mars 1971 Planning Charts of South Polar Regions
(G. de Vaucouleurs).



NOTE: North Pole at all areographic longitudes.

Fig. 7. Regression curve of the North Polar Cap and Hood, mean 1905-1965 (Fischbacher et al., 1969).

than 10° (in late summer). These major remnant white islands are named after the underlying areas they occupy: Ierne ($\sim 137^\circ$ W), Lemuria or Olympia ($\sim 200^\circ$ W) and Cecropia ($\sim 297^\circ$ W). The mean positions of their centroids, which are approximately the same year after year, were given by Capen and Capen (1970). See Table 2. The locations and successive shapes and sizes of the white islands and of the residual summer cap can be seen in the series of schematic maps (Figs. 16 through 19) illustrating the seasonal evolution of the North Polar Cap as prepared by Capen (1972) especially for this review.

SEASONAL BEHAVIOR OF CLOUDS AND WHITENINGS

Outside those of the polar hoods, very few seasonal patterns of meteorological activity have been established so far. Three additional categories of seasonal meteorological activity which have been gradually defined in recent years are:

- 1) Whitenings (surface frost or fog)
- 2) Seasonal and recurrent white clouds (orographic afternoon clouds and localized persistent clouds)
- 3) Great yellow clouds (major dust storms)

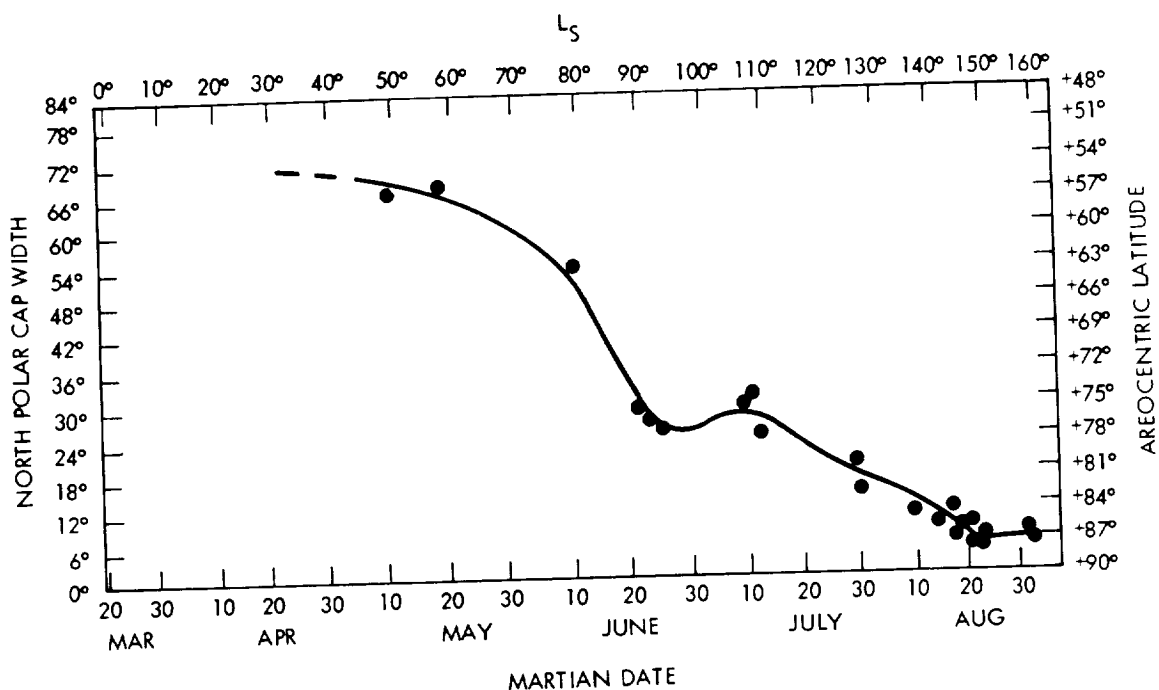


Fig. 12. North Polar Cap micrometric regression curve, 1968-69 (Capen and Capen, 1972).

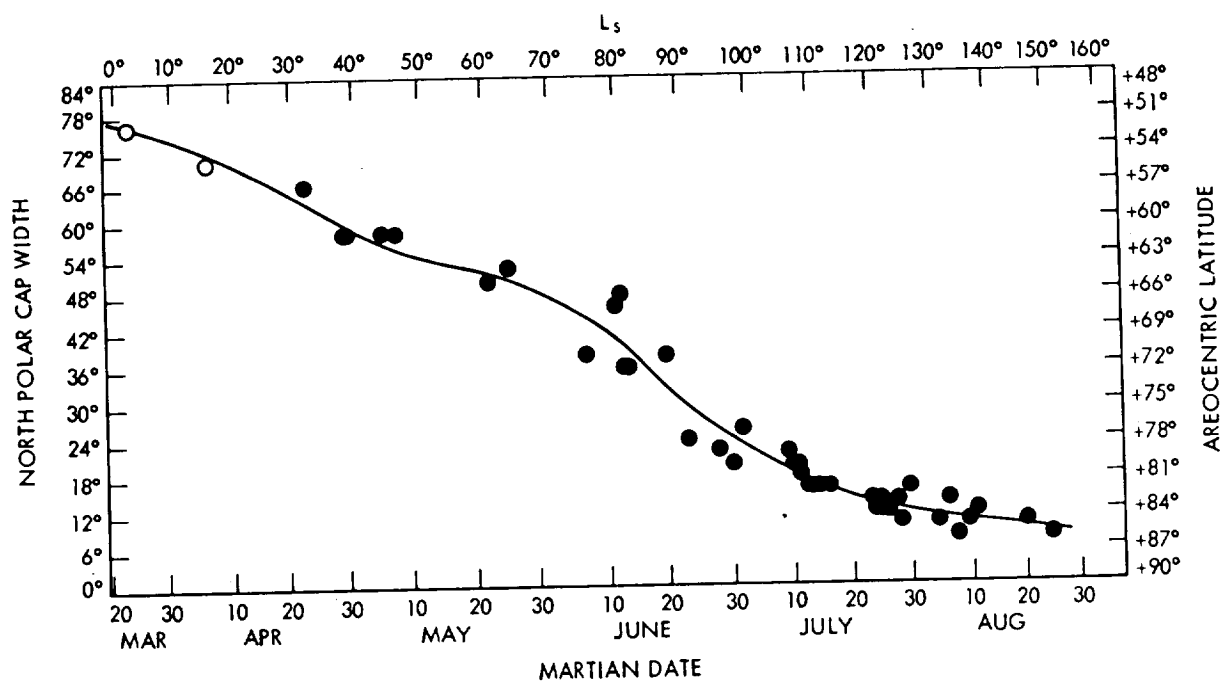


Fig. 13. North Polar Cap photographic regression curve, 1966-67 (Capen and Capen, 1970).

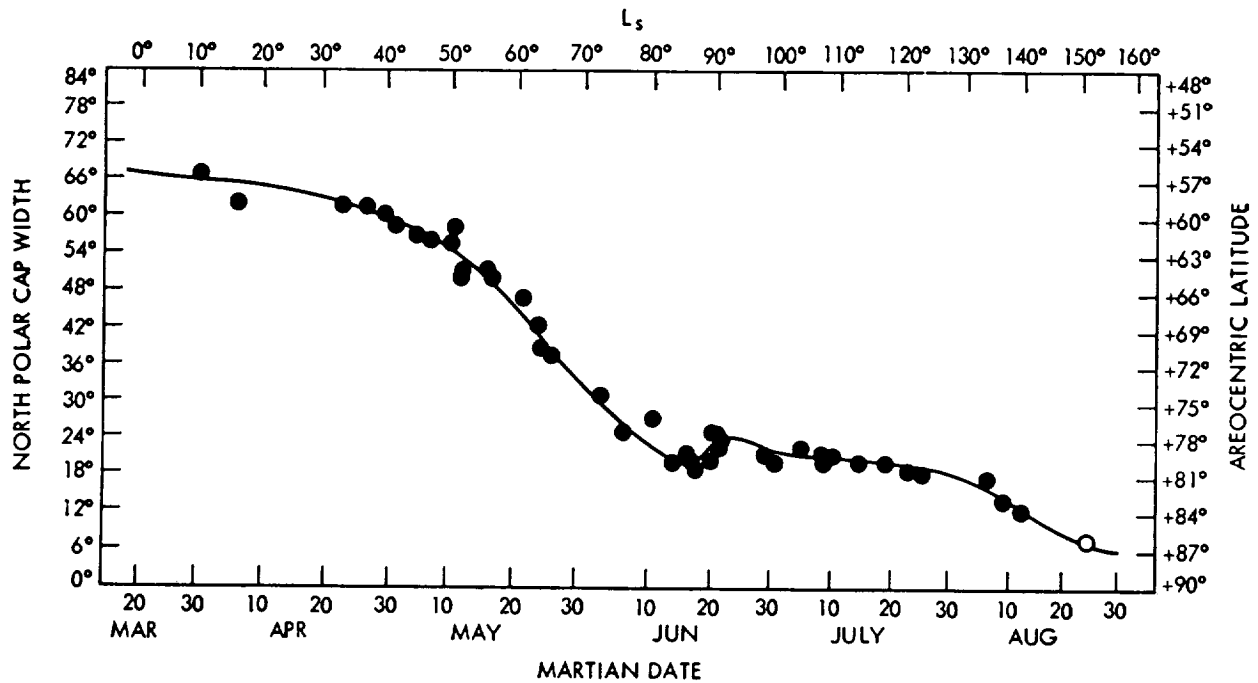


Fig. 14. North Polar Cap photographic regression curve, 1964-65 (Capen and Capen, 1970).

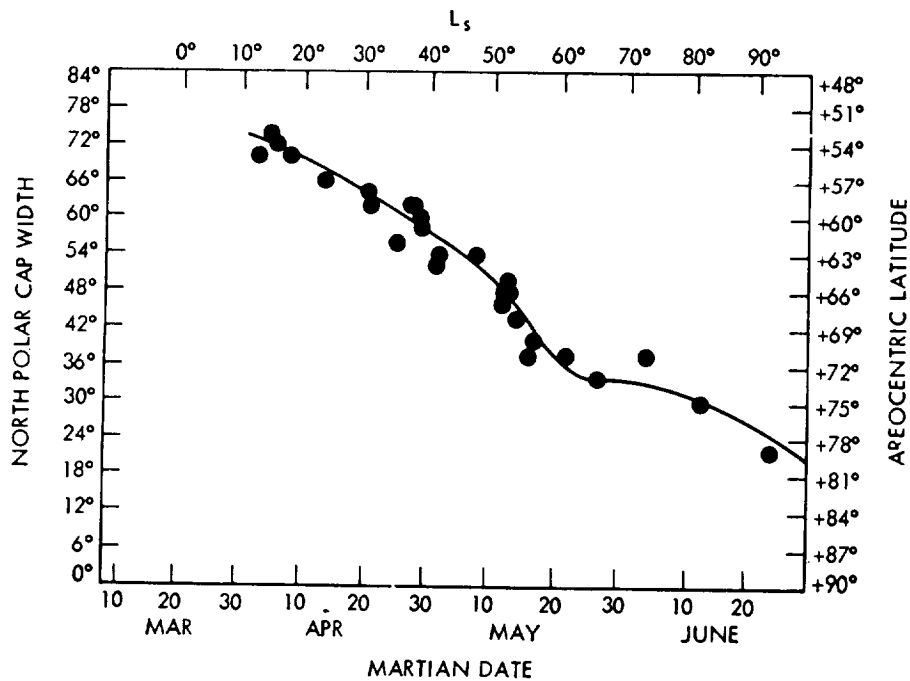


Fig. 15. North Polar Cap photographic regression curve, 1962-63 (Capen and Capen, 1970).

Table 1. North cap regression rates 1962-1969 (areocentric degrees per Martian days) (Capen and Cave, 1971)

<u>Apparition</u>	<u>Early Spring</u>	<u>Max. Rate</u>	<u>Early Summer</u>	<u>Mid-Summer</u>
1962-63	1°/10d	1°/3d	1°/8d	—
1964-65	1°/23d	1°/3d	1°/6d	1°/30d
1966-67	1°/15d	1°/4d	1°/10d	1°/30d
1968-69	1°/20d	1°/2d	1°/7d	1°/20d

Table 2. Mean areographic longitude of centroid of white island remnants of summer North Polar Cap (1879-1968). (Capen and Capen, 1970)

<u>Observer</u>	<u>Ierne</u>	<u>Lemuria</u>	<u>Cecropia</u>
G. Schiaparelli, 1879-88	121°	208°	310°
P. Lowell, 1901-5	122°	206°	311°
E. M. Antoniadi, 1903-29	122°	208°	309°
M. Maggini, 1918-35	136°	213°	278°
A. Dollfus, 1946-52	142°	227°	292°
C. and V. Capen, 1962-68	140°	196°	290°

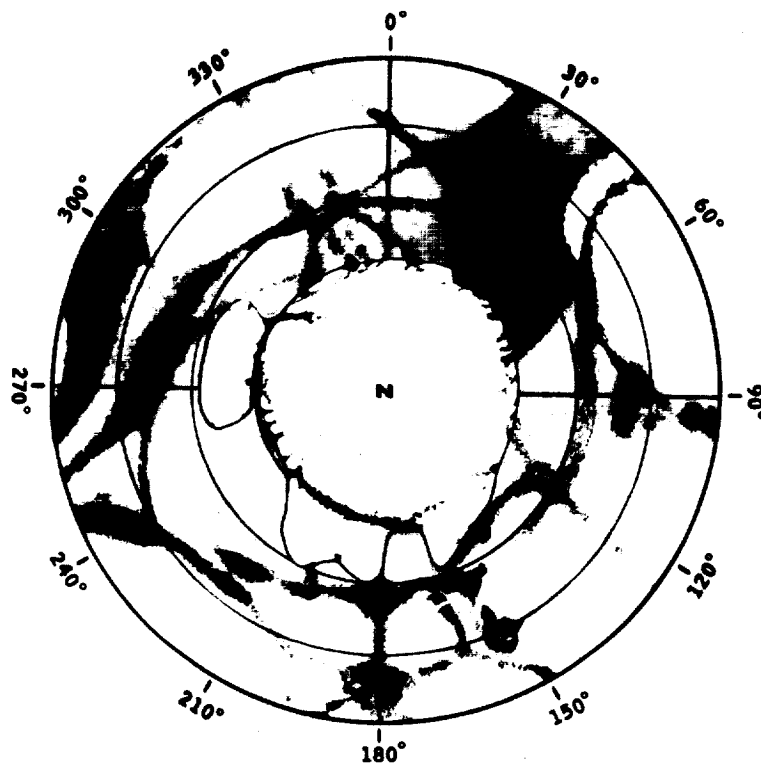
Our knowledge of Martian seasonal meteorological activity is still very limited for the basic reason that apparitions have generally been covered only for a few months centered on opposition. A reconstruction from a full 15-17 year cycle of oppositions therefore yields a rather uncertain general picture over a Martian year. (This is of course true also for surface changes, but it is much more so for the highly variable and often elusive meteorological changes.) Another important fact, especially pertinent to meteorological phenomena (since these are best detected and identified with the use of color filters), is that a systematic colorimetric procedure using a variety of well-defined filters did not come into widespread use in planetary observing practice until recently. (An exception has been the work done at Lowell Observatory by Slipher who pioneered filter photography of planets about 1905.)

The cloud overlays of Figs. 8 through 10 give areographic locations of the center of many clouds — white (O) or yellow (◐) — reported in the different seasons.* Since the compilation is by no means exhaustive nor homogeneous in coverage (through the last 100 years of observational record searched), these overlays cannot be considered as very representative of the clouds' seasonal frequencies. Thus, the northern autumn-winter overlay indicates more clouds, but this is probably biased by the fact that more observations have been made at the more favorable (near-perihelic) oppositions.

*Diversified sources were used for the cloud overlays, the most important were: Slipher (in Annals of Lowell Observatory), Antoniadi (1930), Focas and Dollfus (many reports since 1948), Wells (1966), Capen (many reports since 1954), de Vaucouleurs (many reports since 1937), Miyamoto, etc.

White Clouds and Hazes

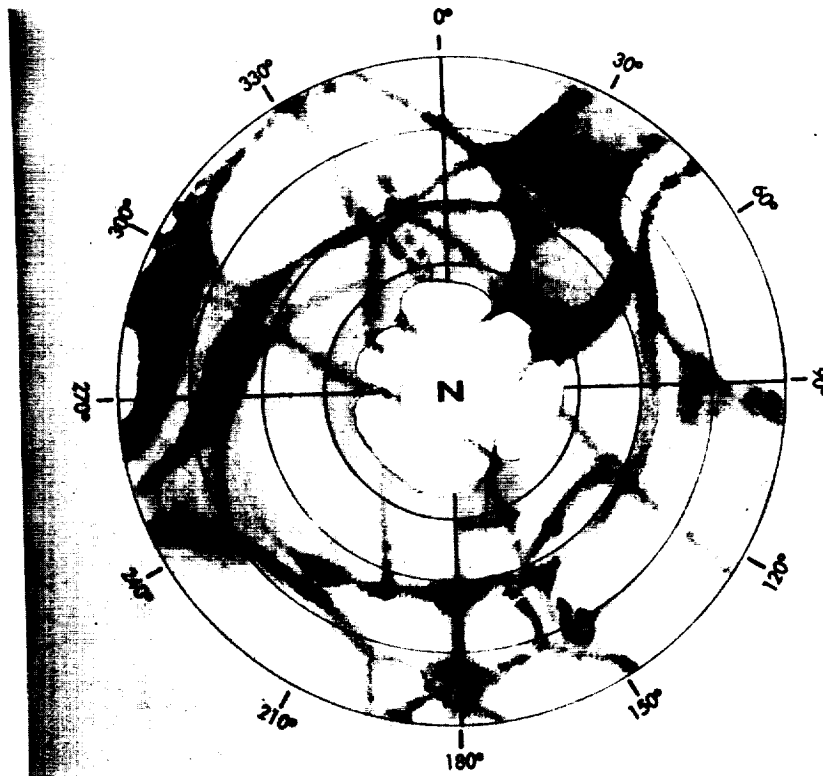
To supplement the dearth of 'continuous' information over one Martian year, Capen and Capen (1972) undertook an unusually lengthy filter photographic and visual patrol of Mars for a period of 20 terrestrial months, centered on the April 15, 1967 opposition. Their 1966-1968 Mars apparition covered close to one full Martian year, from $L_S = 5^\circ$ to 326° (only the second part of northern winter was excepted). They placed particular emphasis on recording the



Northern Mid-Spring ($L_S = 60^\circ$)

The map was produced from 1963 observations made with the JPL Table Mountain Observatory 16-inch Cass. reflector.

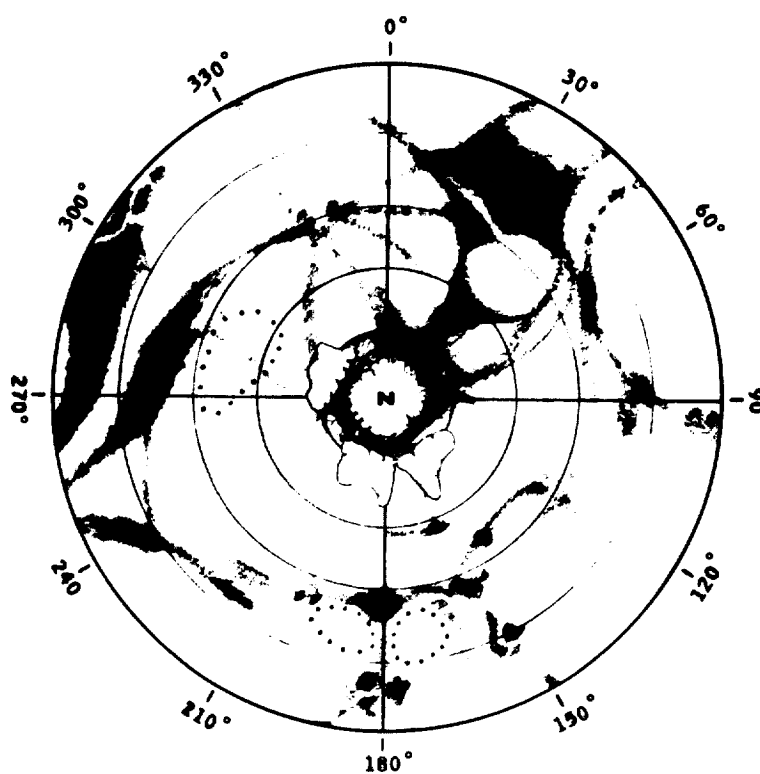
Fig. 16. Seasonal evolution of the North Polar Cap (Capen, 1972).



Northern Summer Solstice ($L_S = 90^\circ$)

The map was produced from 1969 observations.

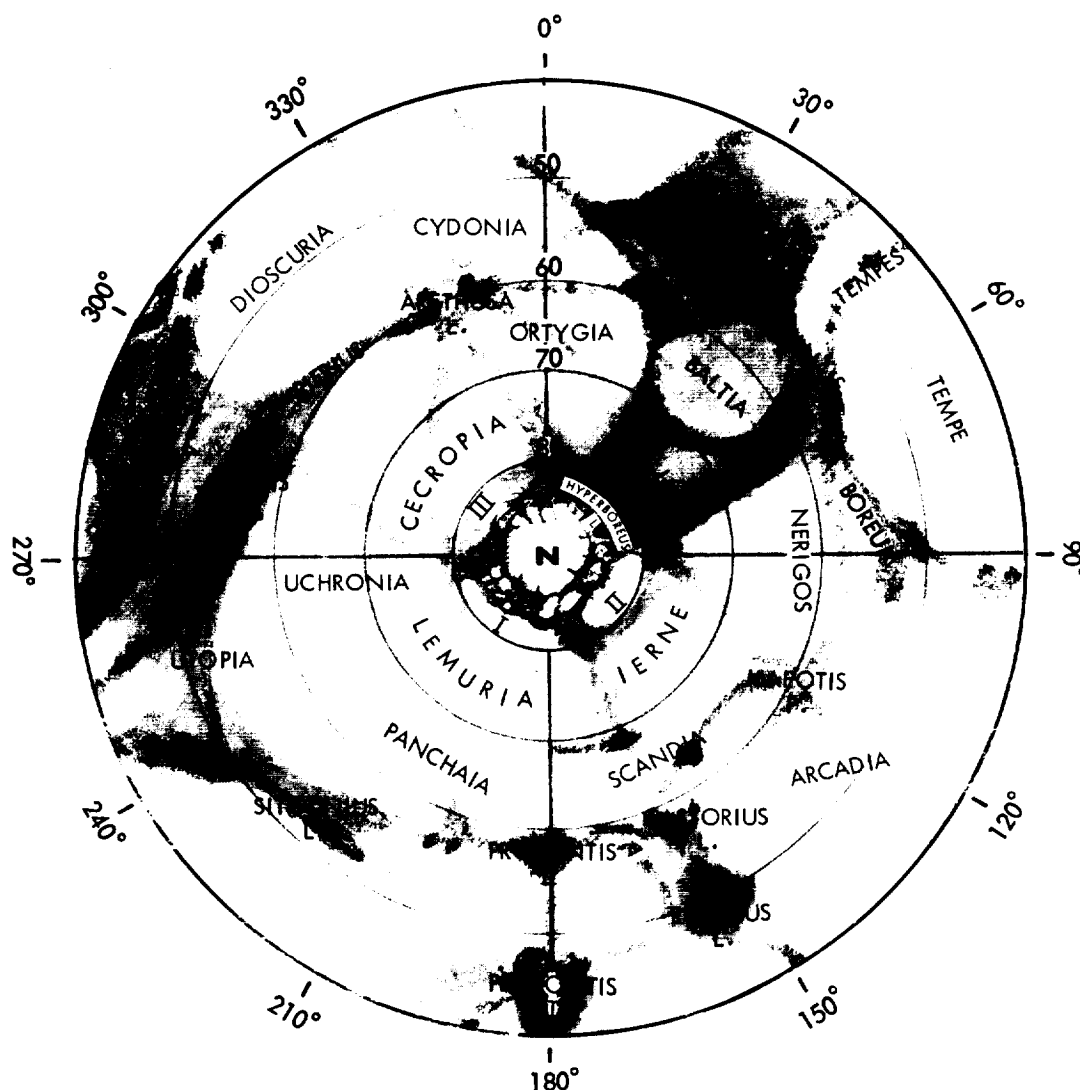
Fig. 17. Seasonal evolution of the North Polar Cap (Capen, 1972).



Northern Mid-Summer ($L_S = 140^\circ$)

The map was produced from 1967 observations.

Fig. 18. Seasonal evolution of the North Polar Cap (Capen, 1972).



Northern Late-Summer ($L_S = 160^\circ$)

The map was produced from observations made with the JPL Table Mountain Observatory 24-inch reflector and the McDonald Observatory 82-inch reflector. The three North Polar Cap residual white areas are labeled: I Lemuria (Olympia), II Ierne, and III Cecropia.

Fig. 19. Seasonal evolution of the North Polar Cap (Capen, 1972).

meteorological activity. Table 3 gives their seasonal comparison statistics* for white clouds and hazes. For nonpolar regions, the results are as follows:

- 1) The Northern Hemisphere definitely had more clouds and hazes throughout the year than the Southern Hemisphere, and particularly in Northern autumn and spring.
- 2) The afternoon limb was considerably more covered by clouds and hazes than the morning limb especially during Northern autumn, winter and even summer.
- 3) The recurring (mostly afternoon) clouds, however, started appearing in Northern late spring and were frequent throughout summer while decreasing in early autumn.
- 4) Cloud bands (mostly equatorial) appeared only during Northern spring and summer.

It should be noted that for this apparition the Northern Hemisphere was best observed from Earth.

Seasonal and Recurrent White Clouds

There are two types of seasonal white clouds known which recur over the same areas of Mars from year to year: the "orographic white clouds," which recur diurnally in the afternoon at the same spot, and the "localized white clouds," which persist for days, shifting in positions around specific areas.**

- 1) Orographic White Clouds (afternoon clouds)

These recurring white clouds form in the early afternoon over small areas of the surface, and produce patterns, such as the famed "W" in the Tharsis region, during spring and summer apparently in both hemispheres. Usually, but not always***, they are located in the tropics. They grow larger and brighter by sunset, and as a rule do not reappear at the morning terminator (one exception has been recorded however, by Capen). They are described in Section 4.1 as blue-white clouds, although they sometimes photograph well in yellow-green. The formation of these clouds appears definitely linked to the topography and special meteorological conditions in spring or summer (see Wells, 1967). The "W" cloud seen by Mariner 1969 was not solid CO₂, according

*Percentages given refer to percentages of observing nights (from total), when the listed meteorological phenomena occurred.

**Capen, in his reports, has called the first "recurrent or recurring afternoon clouds" and the second "seasonal clouds in the classical sense."

***Capen found them restricted to the zone -10° to +40°.

Table 3A. Seasonal meteorological activity, 1966-1970[†]
(Capen and Capen, 1972)

	Spring L _s 0°-90° (%)	Summer L _s 90°-180° (%)	Autumn L _s 180°-270° (%)	Winter L _s 270°-360° (%)
Arctic	30.6	78.7	98.0	100.0
Antarctic	72.1	100.0	13.6	10.0*
Northern hemisphere	84.2	90.4	92.8	97.2
Southern hemisphere	50.9	87.5	30.1	80.6*
Morning	77.2	60.3	19.3	33.3
Afternoon	75.4	100.0	74.7	72.2
Cloud band	20.5	30.3	1.2	0.0*
Recurrent cloud (orogenic)	40.8	57.4	18.0	1.0*
[†] Data for the 1969-1970 apparition were incorporated by the authors for more complete coverage. *These percentages are probably more variable during this season due to the unpredictable nature and intensity of yellow storms.				

Table 3B. Relative occurrence of seasonal cloud activity, 1966-1968
(between hemispheres and morning and afternoon).
(Capen and Capen, 1972)

	Spring L _s 0°-90° (%)	Summer L _s 90°-180° (%)	Autumn L _s 180°-270° (%)	Winter L _s 270°-360° (%)
Northern hemisphere	70.8	57.9	79.0	65.3
Southern hemisphere	29.2	42.1	21.0	34.7
Morning	48.2	40.7	19.2	32.6
Afternoon	51.8	59.3	80.8	61.4

to the analysis by Leovy, who went on to speculate that it could be the condensation product of H_2O vapor percolating up from the ground warmed by the noon insolation maximum. (A quantitative discussion is found in Leovy et al., 1971.)

Besides this conspicuous "W cloud" repeatedly observed (see Slipher, 1962, for example) in southern spring-summer, a number of other examples of orographic clouds were reported by Capen (1966, 1970) who particularly monitored the Northern Hemisphere. Areas conducive to orographic cloud formation included: Elysium, Nix Olympica, Ascraeus Lacus, and an area at $+40^\circ$ in Arcadia. Other such regions are Hellas in the Southern Hemisphere, Edom and Eden near the equator, and the Candor-Tharsis region where Capen again detected the "W" formation in northern spring-summer (thus the "W" group seems to be bi-seasonal).

2) Localized White Clouds

Recurring regionally and seasonally, these dense, whitish clouds of limited extent, persist for days but with displacement within the region. White at first (the clouds are best seen however through blue and blue-green filters) their color changes somewhat, becoming prominent in green, and sometimes visible in yellow. This led Capen (1972) to suspect they might be combinations of white and yellow clouds.

One remarkable example of such localized white clouds was retraced by Capen (1972) as far back as 1911: the Libya-Crocea-Oenotria cloud, which recurs every Martian year at about the time of northern summer solstice and lasts through the first part of summer (L_s : 88° to 140°), circulating around Syrtis Major (sometimes even reaching its northern tip). The prominently dark-blue Syrtis Major changes to light blue, and may even partially disappear, perhaps the result of an important seasonal atmospheric change.

Great Yellow Clouds (major 'dust storms')*

While smaller yellow clouds, as uncommon as they usually are, have been reported in almost any season (see overlays of Figs. 8-10), all of the reported giant or "great" yellow clouds, obscuring large parts of Mars, have occurred only during southern late spring and summer (according to preliminary results of searches of the observational records; see for instance Capen (1971), or Capen and Martin (1972). These major storms probably recur every Martian year at about that time. They seem to start suddenly when Mars is near its perihelion ($\eta = 335^\circ$, or $L_s = 250^\circ$), as for example, in 1956, August 19 ($L_s = 248^\circ$), in 1971, September 22 ($L_s = 259^\circ$). Once started, these storms may actively develop, sometimes expanding planet-wide (as in 1971) and may persist for weeks or even a few months, through the first part of summer, and finally decay and subside (as fine yellow veils) in an equally long period.

*See Table 3, of Sec. 4.1, p. 12

These major yellow clouds or storms may be classified in a 'recurrent' yellow cloud category, regionally as well as seasonally, because the records show their initial phase appears to always be associated with the same (Southern Hemisphere) regions: Hellas-Hellespontus-Noachis and vicinity in particular. (See Capen and Martin, 1971, and 1972.)

The sudden occurrence of major yellow clouds or "dust" storms near the perihelion time and in certain preferred regions located in the zone of maximum insolation* on Mars, strongly points to the seasonal buildup of particularly unstable atmospheric conditions (leading to the onset of strong advection and convection with associated turbulence, vortices, etc). This buildup occurs over thermally and perhaps hygrometrically preconditioned ground, which itself is probably already favored by its topography (location and relief) as well as its physical-chemical properties**. It appears that dust is raised suddenly by some triggering meteorological mechanism at a precise time, and is maintained aloft by a persistent, dynamically exceptional circulation which rapidly enlarges the cloud outburst. Analysis of the 1971 Mariner 9 data may not clarify the exact triggering mechanism, since the global dust storm had already been in progress for 6 weeks before the arrival of the spacecraft. ($L_S = 290^\circ$, Nov. 10, 1971, first pre-orbital TV pictures).

Whitening Areas

Many areas of Mars exhibit a conspicuous whitening which appears to be seasonal, although there may be a diurnal effect superimposed. The whitening (as seen at the telescope) may last all day, or may not, depending upon seasonal time. In the latter case, the white patch is seen to be brightest in the early morning, as if formed during nighttime, and gradually fades away with the heating rays of the Sun. Most whitenings occur during one season, lasting sometimes two successive seasons and a few even three seasons (Hellas). According to Capen and Capen (1970), white areas are usually more prevalent at a time when the polar cap of the same hemisphere is rapidly regressing, that is around summer solstice time (a notable exception is Hellas). Some areas whiten during two separate seasons: for example, Elysium, Nix Olympica, Tharsis, etc. Capen (1972), who has devoted much time since 1962 in observing and recording whitening areas, noted that the second whitening seems to correlate with the rapid regression of the other polar cap; only a systematic study could confirm this. So far, only sketchy or incomplete information is available on the seasonal activity of white areas. The survey by Capen and Capen (1970) for the 1967 apparition yielded the following percentages of observing nights when whitenings occurred: spring 24%, summer 66%,

*The thermal equator is then at about -24° latitude.

**Comparison of the 1956 and 1971 cases by Capen and Martin 1971, disclosed that the behavior of the atmosphere prior to their formation was "somewhat alike" (little white cloud activity, and high contrast of surface features).

autumn 10%, (winter: insufficient data). The observations, both visual and photographic were made with filters ranging from blue-green to near infrared.

A list of all whitening areas detected and charted by Capen and Capen (1970) during their 1962 to 1968 observations is contained on Fig. 20 which locates many of these on Capen's 1967 base map of Mars. The whitenings are seen to generally affect the light* areas of Mars' surface and are not restricted by latitude in either hemisphere (while the "afternoon clouds" seem mostly restricted to tropical latitudes). Thus, they are widely distributed over Mars, but affect only preferred areas. In these areas, the topographical, thermal, and meteorological conditions become, at certain times of the year, favorable to condensation of a common volatile. The whitening formed is apparently either an actual surface deposit (frost) or a near-surface dense fog (ground fog), or both.** The condensing volatile is presumably H₂O vapor, but this has yet to be demonstrated. Condensation of CO₂ is less likely because of the extremely low temperatures required (below ~148°K). However, one may envisage condensation of both H₂O and CO₂, or only CO₂ at the higher latitudes.

THE WAVE OF DARKENING

The wave of darkening has been described as "a progressive albedo decline of the Martian dark areas (but not the bright areas) starting in local springtime from the edge of the vaporizing polar ice cap, and moving toward and across the equator" (Sagan and Haughey, 1966). There is quantitative evidence that dark areas darken during the Martian spring, reaching maximum darkness after the summer solstice. Whether the darkening occurs as a "wave" from the pole has been argued. A statistical analysis by Pollack, Greenberg, and Sagan (1967) showed that while there are areas which "violate the concept of an invariable wave," there is "a very significant correlation of latitude with time of maximum darkening."

The waves start alternately from the two polar caps at half-year intervals, cross the equator, and fade at about 22° latitude in the opposite hemisphere from which they began (Focas, 1962). The rate of propagation is variable but averages about 35 km per day. The time from beginning of darkening to maximum darkening is 0.30 to 0.35 Martian years in the circumpolar and temperate areas, 0.30 years at the boundary of the equatorial zone, and 0.15 years in the equatorial area (Focas, 1962). The total duration of darkening — minimum to maximum and fading back to minimum — is 0.67 Martian years in the circumpolar areas, for the wave proceeding from the North Cap, and 0.55 years for the north wave, at its southern limit. The wave proceeding from the

*The white areas as shown in Fig. 20, which was primarily derived from visual observations, generally do not encroach over bordering dark areas.

**de Vaucouleurs (1971) cautions that not all early morning white patches are frost deposits on the surface and that "at least some are due to high-altitude icy haze (or in some cases dust layers), the elevation of which can be estimated when the cloud is completely or, more often, partly detached from the terminator." He cites some rare examples of clouds projecting at the sunrise terminator.

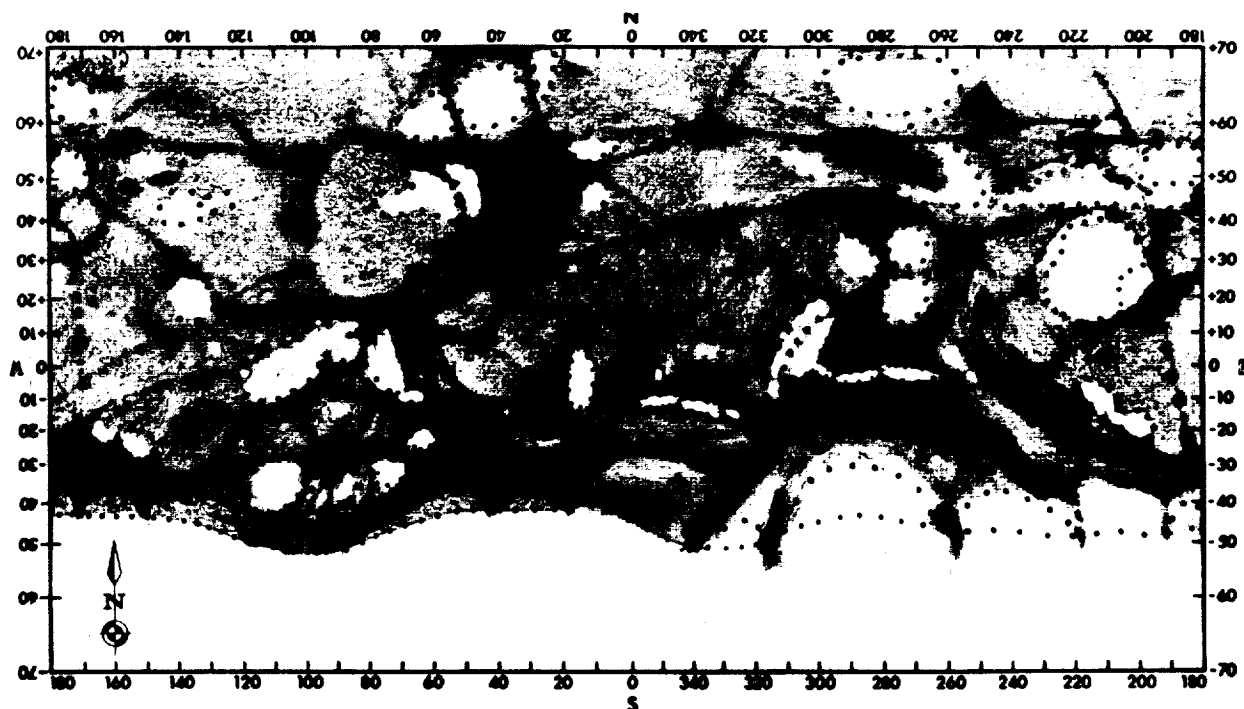


Fig. 20. Schematic base map of Mars 1967* showing whitening areas detected in 1962-1968 by Capen and Capen (1970).

Note: The list of whitening areas observed is given below with approximate coordinates of their centroids:

Abalos (030, +85), Aeolis (212, -10), Aeria (310, +18), Aethiopis (245, +08), Albor (205, +22), Amazonis (145, +22; 170, +22), Aram (015, 00), Arcadia (Alba) (115, +50), Argyre I (030, -45), Ausonia (250, -45), Azania (185, +36), Baltia (040, +65), Candor (075, +08; 078, +20), Cebrenia (215, +42), Cecropia (290, +75), Chryse (038, +02), Claritas (100, -30), Crocea (290, -02), Daedalia (122, -12), Deucalionis Regio (345, -11), Dia (090, -60), Dioscuria (310, +52), Edom (350, -02), Electris (180, -45), Elysium (215, +30), Eos (040, -10), Eridania (215, -45), Hammonis Cornu (315, -10), Hellas (295, -45), Hellespontus (328, -42), Ierne (140, +80), Isidis Regio (280, +20), Lemuria (Olympia) (185, +80), Lemuria (235, +75), Libya (275, 00), Memnonia (165, -20; 155, -05), Meroe Insula (295, +35), Neith Regio (275, +35), Nix Cydonia (015, +45), Nix Lux (112, -08), Nix Olympica (135, +26), Nix Tanaica (048, +50), Noachis (345, -40), Nymphaeum (305, +08), Ogygis Regio (065, -48), Ophir (068, -08), Ortygia (015, +55), Oxia (018, +30), Panchaia (250, +62), Phaethontis (135, -45), Phlegra (192, +48), Propontis Quadrangle (170, +50), Scandia (160, +68), Scandia-Boreum Mare (110, +80), Sinai (062, -25), Syria (090, -15), Tempe (065, +47), Tharsis (100, +02), Thaumasia (075, -30; 090, -40), Utopia (265, +52), Uchronia (260, +60), Xanthe (050, +15), Zephyria (190, -08).

*Ref.: Capen, C.F., A 1967 photovisual chart of Mars: J. ALPO, v. 22, nos. 7-8, August.

South Cap lasts 0.50 Martian years in the circumpolar area and 0.40 years at its northern limit (Focas, 1962). *

The average "intensity" of dark areas on Mars increases from pole to equator. The additional intensity resulting from the wave of darkening decreases from poles to equator. This is balanced by the fact that two waves affect the equatorial regions. The behavior of the wave of darkening is shown diagrammatically in Fig. 21 taken from Focas (1961), which indicates dark areas affected. An average behavior is also shown on a separate overlay for Figs. 9 and 10.

The seasonal variation of polarization (differences between dark and bright areas) is likewise shown in Fig. 22, taken from Dollfus (1961). It indicates that the variations take place principally during spring and summer in each hemisphere and are maximized at the end of spring.

The photometric and polarimetric curves of Focas and Dollfus, which exhibit a very definite seasonal relationship to the sublimating-regression of the spring-summer caps, quantitatively depict the wave of darkening phenomenon presumed to exist on Mars.

The cause of the wave of darkening was commonly attributed in the past to water vapor, released from the vaporizing polar cap, that somehow interacted with the surface material or with "vegetation" to cause the darkening. Other explanations, which now (since about 1965) have gained in favor, generally involve seasonal transport of dust on and off of dark areas. See for example the Sagan and Pollack (1967) "windblown dust" theory. Both classes of explanation of the wave of darkening are only hypotheses. Pollack, Greenberg, and Sagan's (1967) statistical analysis is unable to differentiate between the two hypotheses. At present, the wave of darkening remains one of Mars' greatest enigmas.

The reality of an actual "wave" of darkening sweeping down from regressing pole to equator has been seriously questioned in very recent years (since about 1969) by B. Smith of NMSU, and by W. Baum and C. Capen of Lowell Observatory, for example. They claim that extensive examination of photographic records (such as Lowell Observatory's collection of Mars plates) reveal no convincing evidence for the existence of a darkening wave.** However, it appears that the study was only cursory (a systematic analysis requiring much more work), and therefore it is too early to consider this view here.

*Focas (1962) pointed out that under the highest telescopic resolutions, the dark areas resolve into a mottled pattern of small dark spots or nodes of the order of 100-km across, on a dusky background; and that it is these nodes that do the darkening.

**Interestingly, some evidence of the inverse phenomenon, a seasonal brightening of (adjacent) bright areas, was obtained recently through photoelectric scanning of the disk (Boyce and Thompson, 1971). This would confirm what Capen earlier (1967-1969) had detected through densitometric measurements of photographic plates.

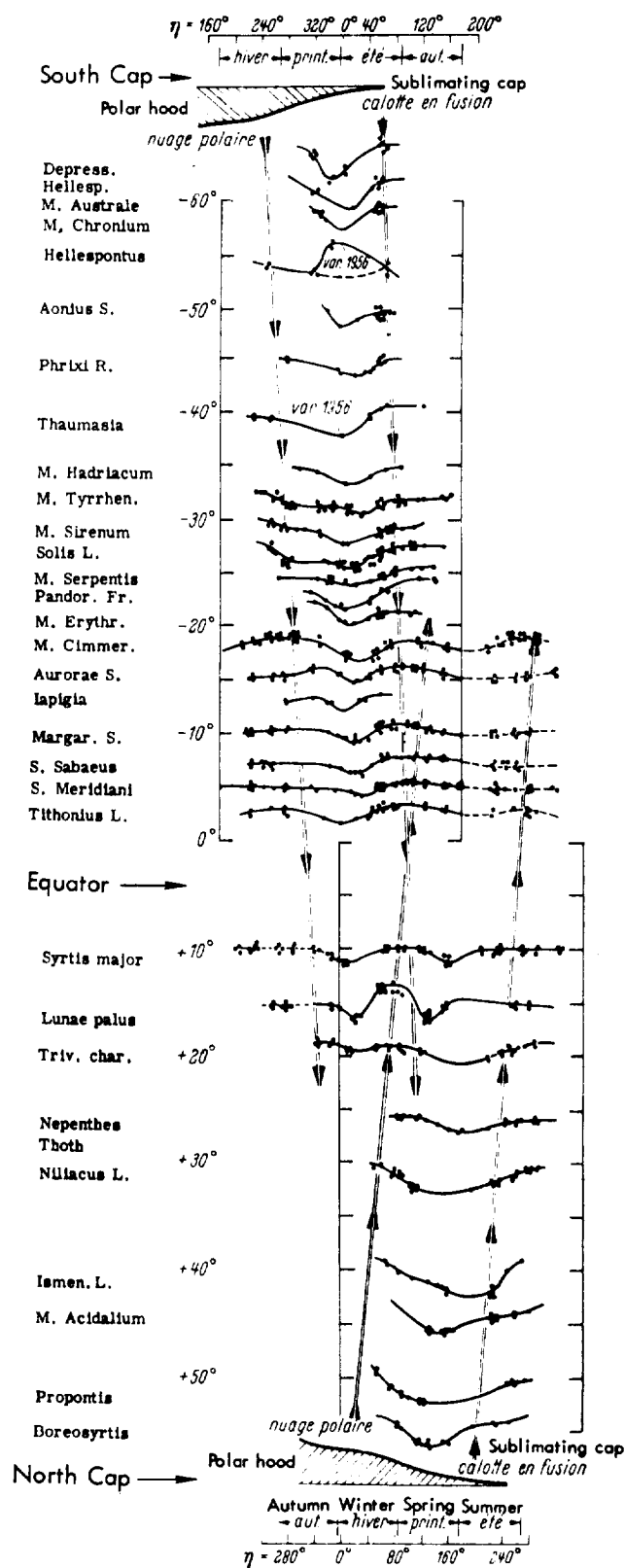


Fig. 21. The seasonal waves of darkening of the dark areas of Mars according to the photometric data of Focas. The waves are seen to stem alternatively from the two poles and fade out as they reach about 22° in the opposite hemisphere (Focas, 1961).

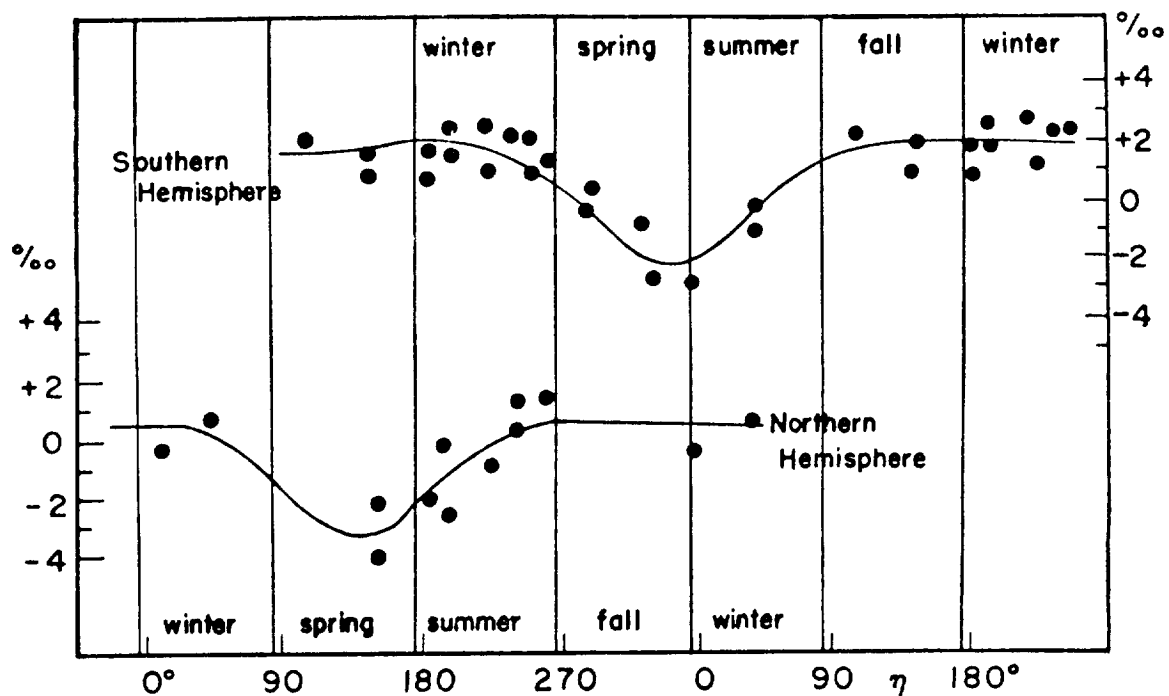


Fig. 22. Mars, seasonal variation of polarization. Polarization differences between dark markings and orange deserts, for phase angle $\alpha = 25^\circ$, plotted against heliocentric longitude (Dollfus, 1961).

SEASONAL BEHAVIOR OF SURFACE FEATURES

The wave of darkening is a statistical phenomenon differing in its effect from area to area, and is in no sense an absolute description of even the behavior of intensity of all dark areas. Besides such albedo changes, there are color changes and changes in shape, size, and internal appearance of the various dark areas. Bright areas also show seasonal changes in color and sometimes in structure. These changes in individual northern equatorial and polar areas have been summarized in Tables 4 through 7* prepared by C. Capen for this document. Tables 8 and 9 (Capen, 1972) give the seasonal changes for the south and north polar regions, respectively.

General Comments on Martian Colors

Winter colors of dark areas tend to be very subdued, often grayish or brownish hues. Lack of contrast sometimes causes features to disappear. Blue-greens, yellow-greens, and blacks appear common in late spring. The 'canals,' which react to the wave of darkening like any dark area, become prominent in spring. Summer is a period of deepening color with changes to purples, browns, and grays, which fade as summer progresses. Fall is a drab period very like winter.

*The regional maps are from the Mars 1969 I. P. P. map produced at Lowell Observatory.

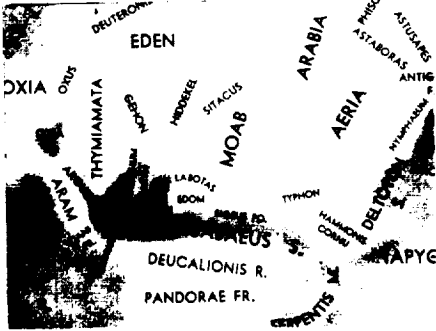
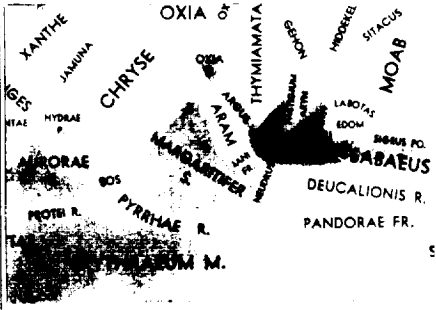
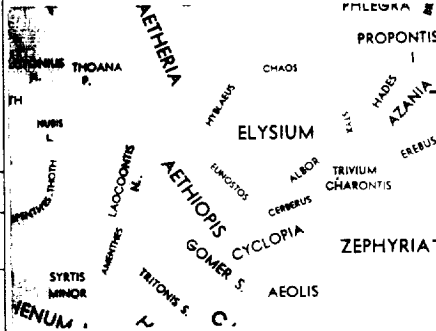
Table 4. Table of seasonal changes in northern dark areas of Mars (Capen, 1972).

Area and location (center of area)	Martian season	Type of change		Map
		Color	Shape and size	
Mare Acidalium +50° latitude, 35° longitude	Spring	Dark gray, blue-gray, with oasis gray-green; gray in general	Boundaries weak	
	Summer	Black-green central area; large, gray- green oases; changes to gray-green at end of summer	Large, swollen in size	
	Fall	Lightens to blue-gray, losing contrast; still dark, variated	Borders fade	
	Winter	Grays and browns	Center fades to match edges	
Niliacus Lacus +32° latitude, 32° longitude	Spring	Dark gray unmapped oasis; <u>late</u> : dark gray	Internal changes in shape; borders and center darken	
	Summer	Dark gray	Swollen in size; looks larger	
	Fall	Dark gray		
	Winter	Gray	Borders weak	
Mare Boreum (Baltia-Boreum) +65° latitude, 85° longitude	Spring	Dark gray; blue tint and black shades as cap melts; black blue		
	Summer	Black-blue		
	Fall	Less contrast; dark gray	Ill-defined borders	
	Winter	Dark gray	Beneath cap	

Table 4. Table of seasonal changes in northern dark areas of Mars (Capen, 1972) (continued).

Area and location (center of area)	Martian season	Type of change		Map
		Color	Shape and size	
Propontis Complex +50° latitude, 170° longitude	Spring	Darker gray	Highly complex changes in shape	
	Summer	Gray black; loses contrast in late summer	Shape: oases swollen, canals dark and seasonal canal structure; Size: larger oases	
	Fall	Dark gray to black	Fading shape	
	Winter	Mid-gray shade	Shape: simple parallelogram with corner oases; Size: small weak oases, not connected	
Nodus Laocoontis- Alcyonius +30° latitude, 255° longitude	Spring	Very active; A: gray-green to black-green; B: small, black-green oasis; C: intense, saturated green; D: not seen	Well defined border, secular changing position toward S. E.	
	Summer	C: black-green, darker	C: most color- saturated (green) on Mars, 1964-65	
	Fall	C: fades, gray-green; others gray		
	Winter	Inactive; A and C seen; medium gray	Changing shape	
Utopia-Boreosyrtis +50° latitude, 270° longitude	Spring	Increase in contrast; dark gray 61 hue	Internal structure changes in size	
	Summer	General: dark blue-gray; mid-summer: intense blue- black with variations, dark browns, olive drabs, ochre	At times yellow cloud changes its shape and appearance	
	Fall	Fading con- trast; dark gray		
	Winter	Dark gray		

Table 5. Table of seasonal changes in equatorial dark areas of Mars (Capen, 1972).

Area and location (center of area)	Martian season	Type of change		Map
		Color	Shape and size	
Meridiani Sinus 0° latitude, 0° longitude	Spring	Dark gray shade		
	Summer	Black shade	Shape: Caret* extension toward Argus; Size: Fastigium Aryn fills in (darkens) between two canal Carets (does not become black)	
	Fall	Dark gray to black	W. Caret dims; no change in size	
	Winter	Sometimes black-blue	Size: Fastigium Aryn becomes light	
Margaritifer Sinus -10° latitude, 25° longitude	Spring	Early: dark gray shade; late: blue-gray hue + dark gray		
	Summer	Dark gray	Internal canal changes in size	
	Fall	Changes to dark gray + mottled brown		
	Winter	Dark gray + mottled dark brown	Ill-defined	
Aurorae Sinus -12° latitude, 60° longitude	Spring	Early: black shade; late: black-blue		
	Summer	Black-blue		
	Fall	Black and dark gray shade		
	Winter	Stays dark		
Trivium Charontis-Cerberus I +15° latitude, 200° longitude	Spring	Medium dark gray and brown tints; olive drab seasonal change takes on intense dark gray	Size: below normal contrast, 1964-65	
	Summer	Stays dark		
	Fall	Dark gray and brown		
	Winter	Medium dark gray and brown tints		

*Term used to designate root-like darkening toward canal.

Table 5. Table of seasonal changes in equatorial dark areas of Mars (Capen, 1972) (continued).

Area and location (center of area)	Martian season	Type of change		Map
		Color	Shape and size	
Mare Cimmerium -30° latitude, 200° longitude (equatorial and southern area)	Spring	Medium dark gray with dark brown and purple		
	Summer	Nondescript medium dark gray with dark brown and medium gray streaks	Well-defined. Hesperia becomes light.	
	Fall	Dark purple-gray		
	Winter	Changes to dark brown with purple-gray streaks	Edges: N. E. Gomer Sinus has been showing secular change.	
Mare Tyrrhenum- Iapygia -15° latitude, 270° longitude	Spring	Purple and dark brown	Carets increase in contrast; no change in shape	
	Summer	No change		
	Fall	Fading purple and mottled brown; also grays	Carets decrease in contrast	
	Winter	Medium gray with mottled brown and yellow-green; most prominent and colorful feature on Mars	Yellow-cloud affects Iapygia	
Syrtis Major +11° latitude, 290° longitude	Spring	Blue-gray <u>late</u> : bright, saturated blue-green		
	Summer	Dark blue-green; <u>late</u> : returns to blue-gray	North tip secular change	
	Fall	Dark blue-gray		
	Winter	Dark gray-blue	Seasonal shift W	
Sabaeus Sinus- Mare Serpentis -10° latitude, 330° longitude	Spring	Dark gray	Size: very stable, high contrast area	
	Summer	Black	Possible S border shift	
	Fall	Dark gray shade	Stable	
	Winter	Black and dark gray	Possible So. border shift. Yellow cloud affects Serpentis	

Table 6. Table of seasonal changes in northern light areas of Mars (Capen, 1972).

Area and location (center of area)	Type of change	Map
Cydonia-Ortygia +50° latitude, 0° longitude	Normal ochre desert color south of Novem Viae in Nix Cydonia; exhibits diurnal seasonal whitening	
Tempe +40° latitude, 70° longitude	Large ochre region; filling-in by Tempes canal (secular); Nix Tanaica exhibits diurnal seasonal whitening	
Arcadia, Scandia +45° latitude, 135° longitude Propontis +50° latitude 180° longitude	Arcadia: large ochre area, over which recurrent afternoon clouds form; yellow dust clouds have been observed Scandia: dark ochre; some seasonal darkening; sometimes filled in, appears similar to maria Propontis complex seasonal darkening. Secular motion E-W and SW	

Table 6. Table of seasonal changes in northern light areas of Mars (Capen, 1972) (continued).

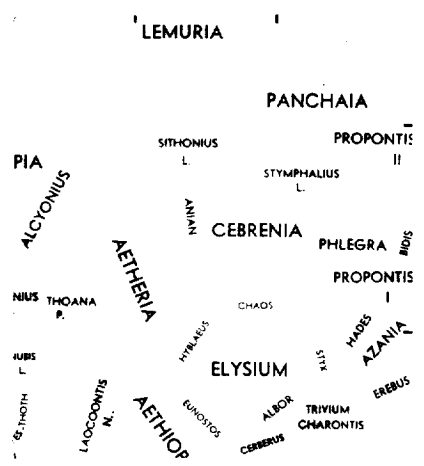
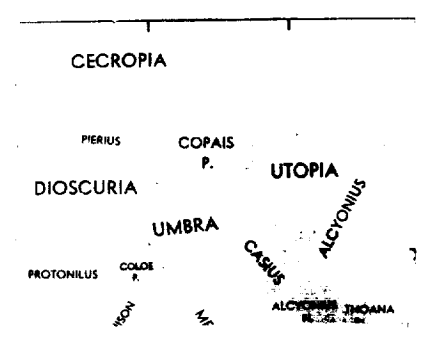
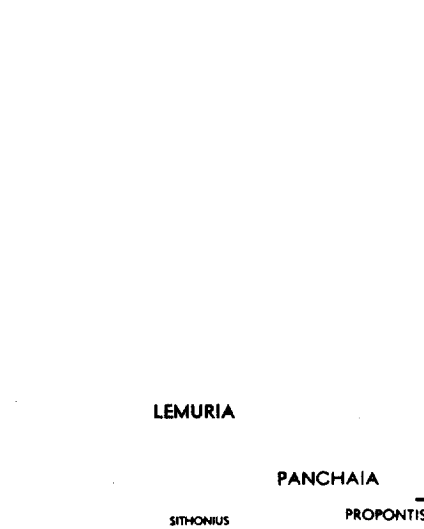
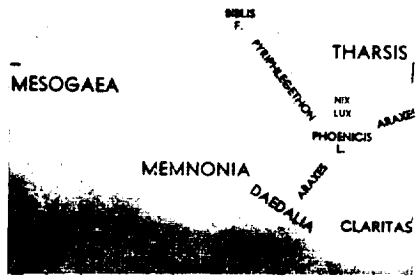
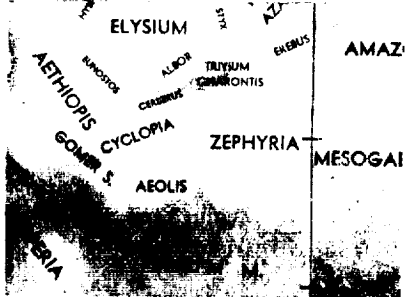
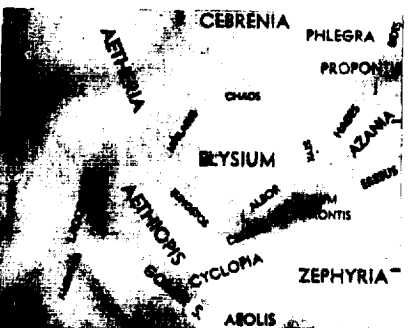
Area and location (center of area)	Type of change	Map
Phlegra, Cebrenia-Aetheria +45° latitude, 210° longitude	Phlegra: variable color hues ranging from light to dark ochre, and yellowish; exhibits seasonal darkening due to filling-in Cebrenia-Aetheria: normal ochre region	 This map shows the northern light areas of Mars. Key regions labeled include LEMURIA at the top, PANCHAI A below it, and PHLEGRA to the right. Other regions shown are CEBRENIA, AETHERIA, ELYSIUM, and AETHIOP. Numerous smaller features and points are marked with letters and names, such as SITHONIUS, STYMPHALIUS, ALCYONIUS, NIOS, THOANA, JUBIS, ETHOTH, LAOCOONIS, EUNOSTOS, ALBOR, TRIVIUM, CHARONTIS, CEBREUS, HAUS, AZANIA, and EREBUS.
Dioscuria +50° latitude, 320° longitude	Normal ochre area; some seasonal whitening	 This map shows a different set of northern light areas. Key regions labeled include CECROPIA at the top, DIOSCURIA in the middle left, UTOPIA in the middle right, and UMBRA below Utopia. Other regions shown are PIERIUS, COPAIS, CASUS, and ALCYONIUS. Smaller features and points are marked with letters and names, such as PROTONILUS, COLOE, and M.
Panchaia-Cecropia +65° latitude, 180-340° longitude Lemuria +70° latitude, 240° longitude	Normally dark ochre region; darkening during spring; light ochre in late summer, fall; covered by polar cap in winter; within Cecropia (+65° latitude, 275-315° longitude) a large, white, oval frost patch has been observed from time to time Lemuria dark when first uncovered by cap	 This map shows the northern light areas of Mars, including regions like LEMURIA at the top, PANCHAI A below it, and CECROPIA in the middle. Other regions shown are UTOPIA, UMBRA, and ALCYONIUS. Numerous smaller features and points are marked with letters and names, such as SITHONIUS, STYMPHALIUS, ALCYONIUS, NIOS, THOANA, JUBIS, ETHOTH, LAOCOONIS, EUNOSTOS, ALBOR, TRIVIUM, CHARONTIS, CEBREUS, HAUS, AZANIA, and EREBUS.

Table 7. Table of seasonal changes in equatorial light areas of Mars (Capen, 1972).

Area and location (center of area)	Type of change	Map
Aram, Chryse, Xanthe +10° latitude, 30° longitude	Aram: light ochre; seasonal whitening Chryse: normal desert ochre hue. Secular darkening 1969 Xanthe: known to whiten in some areas	
Candor - Tharsis +10° latitude, 90° longitude	Light ochre hue; clouds are generated in this region; entire region becomes seasonally whitened	
Syria-Sinai- Thaumasia etc. -30° latitude, 90° longitude Solis Lacus -28° latitude 90° longitude	Variegated colored area with hues rang- ing from dark orange, light ochre, to yellow; seasonal local-area whitening; sometimes covered by yellow clouds Solis L. shifts position and shape seasonally and secularly	
Daedalia -15° latitude, 125° longitude	Normal ochre color; some seasonal darkening.	

Table 7. Table of seasonal changes in equatorial light areas of Mars (Capen, 1972) (continued).

Area and location (center of area)	Type of change	Map
Memnonia-Mesogaea area -10° latitude, 160° longitude	Normal ochre color; seasonal whitening known to occur on southern border of Memnonia	
Amazonis +20° latitude, 60° longitude	Very bland, featureless area (Tempe-Arcadia similar); recurrent cloud activity; Nix Olympica in Amazonis becomes seasonally whitened (historically known); yellow clouds have been observed in this region. A few well defined dark circular oases seen at times.	
Zephyria, Aeolis -10° latitude, 200° longitude	Zephyria: normal ochre color seasonal whitening Aeolis: light region; whitening at times in summer and winter	
Elysium, Aethiopia +20° latitude, 235° longitude	Elysium: normal light ochre (Albor area gray-white); becomes dazzling white during late spring with rapid regression of north polar cap; diurnal retreat of whitening leaves pink tint Aethiopia: normal ochre color dark, transient and secular features	

The color base-maps (Figs. 8 through 10) are based upon filter photography, color photography, and visual studies. Color saturation has been increased to aid reproduction. The maps represent a useful description of seasonal changes on Mars, but again the colors should be accepted with due reservation.

An overlay giving names and locations of prominent Martian features is included and identified as 'Place-Name of Surface Features' and can be used with any of the color base-maps (Figs. 8 through 10). A list of names and coordinates of the features appears as Fig. 11.

Table 8. Table of seasonal changes in south polar region of Mars (Capen, 1972).

Area	Season	Characteristic
Argenteus Mons -70° lat. 40° long.	Winter (N. Hemisphere)	Dark gray and ocher.
	Spring	Medium contrast until covered by winter haze hood.
	Summer	Covered by South Polar Cap.
	Fall	Seasonally bright white with South Polar Cap projection. Later becomes dark.
M. Oceanidum -60° lat. 35° long.	Winter	Dark gray.
	Spring	Very low contrast. Hazy.
	Summer	Covered by winter-type hazes and South Polar Cap.
	Fall	When first uncovered by South Cap it becomes dark.
M. Australe -65° lat. 90° long.	Winter	Dark gray to black. Affected by yellow clouds.
	Spring	Dark gray until covered by winter-type haze.
	Summer	Covered by South Polar Cap.
	Fall	Darkens as South Polar Cap retreats.

Table 8. Table of seasonal changes in south polar region of Mars (Capen, 1972) (continued).

Area	Season	Characteristic
Argyre II -66° lat. 70° long.	Winter	Light ocher, seasonal whitening.
	Spring	Light area until covered by polar hazes.
	Summer	Covered by South Polar Cap.
	Fall	When first uncovered by cap, a dark ocher. Later a light ocher.
Thyles Mons -70° lat. 155° long.	Winter	A light ocher area.
	Summer	Covered by South Polar Cap.
	Fall	Exhibits a bright polar cap projection late fall.
Thyle I and II -65° lat. 160° long. 220° long.	Winter	Light ocher area.
	Spring	Light and ill-defined.
	Summer	Covered by South Polar Cap.
	Fall	Dark ocher hue.
M. Chromium -60° lat. 215° long.	Winter	Varigated dark gray and browns.
	Spring	Dark and ill-defined.
	Summer	Covered by South Polar Cap.
	Fall	Darkens and expands as cap retreats.
Thyle Collis -70° lat. 230° long.	Winter	Light ocher area.
	Summer	Covered by South Polar Cap.
	Fall	Retains a bright cap projection.
Promethei S. Chersonesus Euripus I -63° lat. 260° long.	Winter	Dark gray.
	Spring	Ill-defined.
	Summer	Covered by South Polar Cap.
	Fall	Appears dark when uncovered by South Polar Cap.

Table 8. Table of seasonal changes in south polar region of Mars
(Capen, 1972) (continued).

Area	Season	Characteristic
Novissima Thyle -70° lat. 325° long.	Winter	A dark brown and gray area.
	Summer	Covered by South Polar Cap.
	Fall	A bright cap remnant known as Mountains of Mitchel.

Table 9. Table of seasonal changes in the north polar region of Mars
(Capen, 1972).

Area	Season	Characteristic
M. Baltia +63° lat. 40° long.	Winter	Covered by North Polar Cap.
	Spring	Dark gray when uncovered by cap.
	Summer	Dark ocher.
	Fall	Light ocher.
Hyperboreus L. +80° lat. 55° long.	Winter	Covered by North Polar Cap.
	Spring	Covered by North Polar Cap.
	Summer	Becomes very dark gray and brown and expands as cap retreats.
	Fall	Very dark and partly haze covered.
M. Boreum +65° lat. 95° long.	Winter	Covered by North Polar Cap.
	Spring	Appears dark gray when uncovered by cap.
	Summer	Remains dark.
	Fall	Medium gray and ill-defined.
Scandia +66° lat. 150° long.	Winter	Covered by North Polar Cap.
	Spring	Dark ocher and brown when not covered by cap.
	Summer	Medium to light ocher. Contains a Polar Cap white remnant spot.
	Fall	Light and ill-defined.

Table 9. Table of seasonal changes in the north polar region of Mars (Capen, 1972) (continued).

Area	Season	Characteristic
Panchaia Lemuria	Winter	Covered by North Polar Cap.
+65° lat.	Spring	Dark ocher and brown when not covered by cap.
205° long.	Summer	Light ocher.
	Fall	Light ocher and ill-defined.
Olympia	Summer	White remnant area of North Polar Cap.
+80° lat.	Fall	Light and hazy.
210° long.		
Utopia	Winter	Covered by North Polar Cap
Uchronia	Spring	Utopia dark gray when uncovered.
+60° lat.	Summer	Dark gray.
260° long.	Fall	Light gray and varigated browns.
M. Cecropia	Winter	Covered by North Polar Cap.
+67° lat.	Spring	Dark ocher when uncovered.
305° long.	Summer	Dark to light ocher. Contains a Polar Cap white remnant spot.
	Fall	Light and ill-defined.
Ortygia	Winter	Covered by North Polar Cap.
+65° lat.	Spring	Dark ocher when uncovered.
350° long.	Summer	Medium to light ocher.
	Fall	Light and ill-defined.

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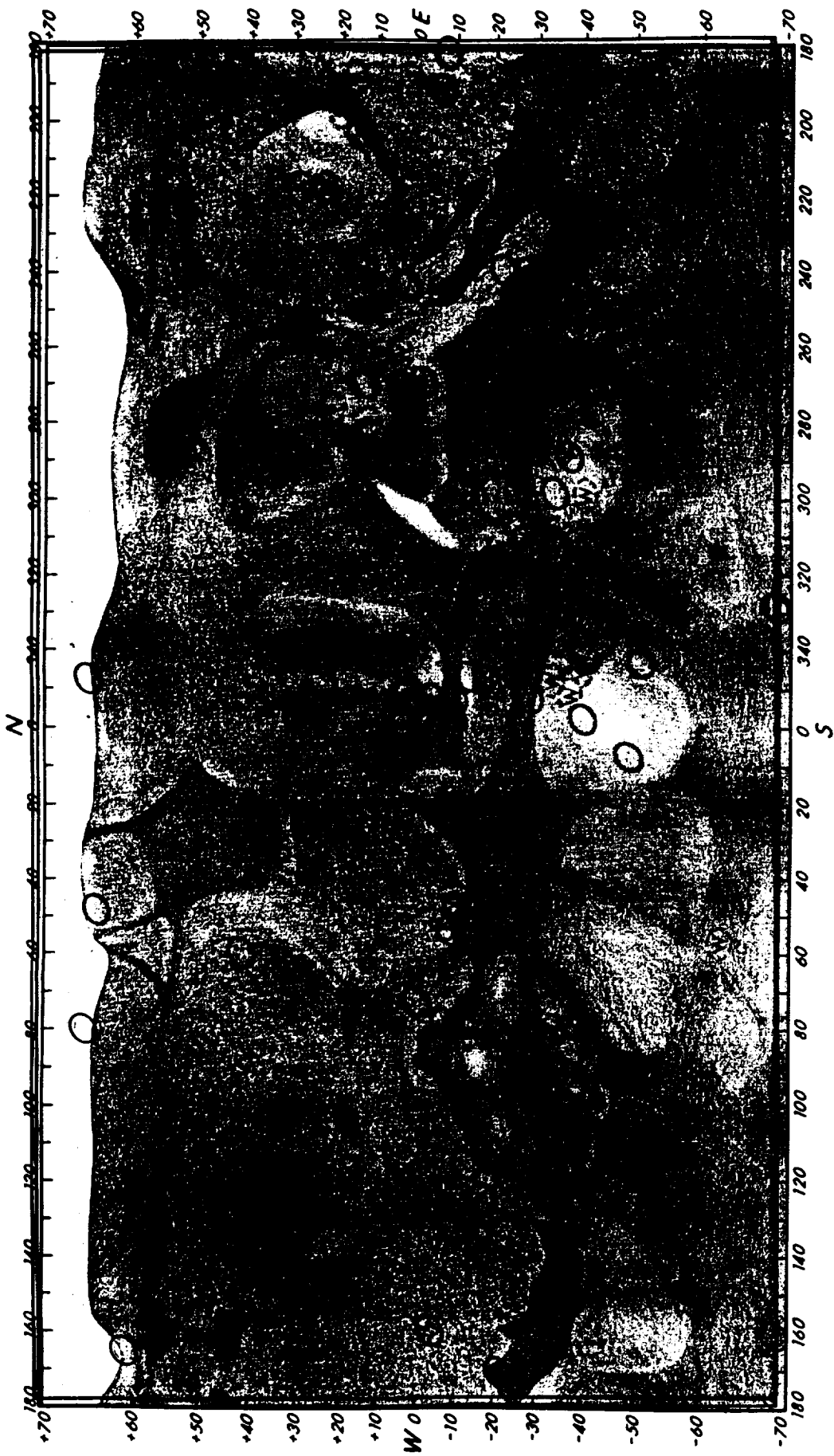
APPENDIX

MARTIAN SEASONAL DATES

Seasonal date is indicated by the value of L_S , areocentric longitude of the Sun, measured in the orbital plane of the planet from its vernal equinox. Thus, $L_S = 0^\circ$ corresponds to the beginning of spring in the Northern Hemisphere, and $L_S = 90^\circ$ to the beginning of summer, etc. (See Fig. 8 in Section 1 on Orbital and Physical Data.)

It is sometimes indicated by η , the heliocentric orbital longitude of the planet, measured from Earth's vernal equinox, or First Point of Aries γ . The relation connecting η to L_S , following the adoption of the Martian equator of de Vaucouleurs (1964) by the American Ephemeris and Nautical Almanac in 1968, is now very nearly: $\eta = L_S + 85^\circ$ (the 85° "constant" deviates very slowly with time, according to the precession of the equinoxes).

Fig. 8. Color map of the Martian surface in northern fall-winter and southern spring-summer, with white and yellow cloud activity during these seasons. The color map was compiled from observational data by C. F. Capen (color contrasts of features were necessarily increased to aid reproduction). The Mercator format was obtained from the International Astronomical Union (Ashbrook, 1958) and from de Vaucouleurs' map (1965) and areographic coordinates (1961a, 1961b, 1962).



WHITE CLOUDS ○
 N. FALL-WINTER, S. SPRING-SUMMER

YELLOW CLOUDS ○
 N. FALL-WINTER, S. SPRING-SUMMER

THE MARTIAN SURFACE
 NORTHERN FALL-WINTER, SOUTHERN SPRING-SUMMER

JPL 608-1
 CALS 608-1
 APRIL 1, 1967

Fig. 9. Color map of the Martian surface in northern spring and southern fall, with wave of darkening, frost, and white and yellow cloud activity during these seasons. The color map was compiled from observational data by C. F. Capen (color contrasts of features were necessarily increased to aid reproduction). The Mercator format was obtained from the International Astronomical Union (Ashbrook, 1958) and from de Vaucouleurs' map (1965) and areographic coordinates (1961a, 1961b, 1962).



WAVE OF DARKENING

N. SPRING, S. FALL

- a: affected every 8 months
- b: at maximum darkening
- c: southern extent of northern wave - see JPL

1969, 1, 1969

WAVE OF DARKENING & N. SPRING, S. FALL

N. SPRING, S. FALL

THE MARTIAN SURFACE

NORTHERN SPRING, SOUTHERN FALL

FROST

N. SPRING, S. FALL

- recurrent frost
- more persistent frost cover
- through the Martian day

1969, 1, 1969

Fig. 10. Color map of the Martian surface in northern summer and southern winter, with wave of darkening and white and yellow cloud activity during these seasons. The color map was compiled from observational data by C. F. Capen (color contrasts of features were necessarily increased to aid reproduction). The Mercator format was obtained from the International Astronomical Union (Ashbrook, 1958) and from de Vaucouleurs' map (1965) and areographic coordinates (1961a, 1961b, 1962).



THE MARTIAN SURFACE

NORTHERN SUMMER, SOUTHERN WINTER

a: northern extent of winter wave

b: at maximum darkening

JPL 808-1
JPL 808-1 1987
C. CAPEN, JPL
APRIL 1, 1987

Notes:

Coordinates listed here for Martian features indicate the approximate center of the feature. The table is an aid in generally locating a feature but should not be considered a source of exact areographic coordinates.

Conventionally, the terms suggesting water are assigned to the darker Martian markings, i.e., Fons (spring), Fretum (strait), Lacus (lake), Mare (sea), Palus (swamp), Portus (harbor), and Sinus (gulf). Those terms applicable to land are usually used for the lighter areas and the bright reddish or yellowish areas, i.e., Insula (island), Promontorium (cape), and Nix (white). Other terms include Depressio (depression) and Regio (region).

[illegible]

Fig. 11. Map and table of Martian place-names and their locations. Map is for use with Figs. 8 thru 10.

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5. ATMOSPHERE

INTRODUCTION

That Mars has an atmosphere was well appreciated by astronomers of the 19th century, who saw a disk with fuzzy edges, brilliant polar caps that came and went, and even what appeared to be clouds or haze that at times obscured the surface. By the turn of the century the great Princeton astronomer, Charles A. Young, had authored a standard textbook which included interpretations of planetary atmospheres. He made the following statement which presents the best opinion available at the time, although by modern standards the reasoning is not exactly flawless:

"This (Mars) atmosphere, however, contrary to opinions formerly held, is probably much less dense than that of the Earth, the low density being indicated by the infrequency of clouds and of other atmospheric phenomena familiar to us upon the Earth, to say nothing of the fact that, since the planet's superficial gravity is less than two fifths of the force of gravity on the Earth, a dense atmosphere would be impossible."*

The atmosphere of a planet is an immensely complex thing, an order of magnitude more complex than an ordinary hot stellar atmosphere where only atoms need be considered. (Some molecules become important in the coolest stars.) Not only does a planetary atmosphere consist largely of molecules, but even matter in liquid or solid state may be present. Furthermore, a planetary atmosphere is in a perpetually nonisotropic radiation field, as insolation varies with planetary rotation and revolution. We have really begun to understand the Earth's atmosphere only as it has been penetrated by aircraft, balloons, and rockets. If we demand perfect accuracy, a "simple" 24-hr weather prediction for a terrestrial city is still beyond our practical capabilities, due to lack of sufficient radiosonde data to properly delineate boundary conditions for the problem and to lack of electronic computers with sufficient speed to solve the equations involved even at the rate at which the physical phenomena are occurring.

Fortunately the real engineering needs of our space program are not so great as our scientific curiosity. In the pages that follow an attempt is made to define those gross atmospheric parameters most needed for a successful entry into the Martian atmosphere and a landing (intact) on the Martian surface. These data will be refined as additional observational and theoretical results become available. Meanwhile, an attempt is made to assess realistically the probable errors in the results presented.

*Young, C. A., 1902, p.361-371 in Manual of astronomy: Mars: Boston, Mass., Ginn and Co.

5.1 ATMOSPHERIC COMPOSITION

DATA SUMMARY

The species C, O, H, H₂O, O₃, CO₂⁺, and CO⁺ have been observed in the Martian upper atmosphere. The isotopes C¹³O₂¹⁶, C¹²O¹⁶O¹⁸, C¹²O¹⁶O¹⁷, C¹³O¹⁶, and C¹²O¹⁸ have been detected in addition to the normal forms of CO₂ and CO. No other atmospheric species have been observationally confirmed to date. However, there are many observational upper limits and theoretical amounts of other species (see text). The abundances of those observed are identified below.

Carbon dioxide, CO ₂	72 ±5 m atm (average over planet). This amount is at least slightly variable with season.
Carbon monoxide, CO	12.5 ^{+8.5} _{-6.4} cm atm.
Water vapor, H ₂ O	0-50 μ precipitable; variable in both time and place (see text and Figs. 1 and 2).
Ozone, O ₃	10 μ atm. This could be ozone trapped in the polar caps, rather than free in the atmosphere (see text).

DISCUSSION[†]

5.1.1 Observed Constituents

Carbon Dioxide

Carbon dioxide was the first (and for many years the only) gas that had been detected spectroscopically in the Martian atmosphere. Kuiper (1952) discovered the relatively strong, $2\nu_1 + 2\nu_2 + \nu_3^*$ (1.57 μ) and $\nu_1 + 4\nu_2 + \nu_3$ (1.60 μ), bands on one of his pioneering spectrometer tracings of Mars made October 7, 1947. He added the discovery of the $2\nu_1 + \nu_3$ (1.96 μ), $\nu_1 + 2\nu_2 + \nu_3$ (2.01 μ), and $4\nu_2 + \nu_3$ (2.06 μ) bands when Mars was near opposition in February 1948. These bands are sufficiently strong to be seen in both Martian and terrestrial atmospheres.

Kuiper's initial attempt to give an abundance took no account of pressure differences between Martian and terrestrial atmospheres and, as he himself

[†]A brief discussion of spectroscopic theory and techniques is given in Section 5.2.

*The "old" band designations for CO₂ are used throughout this document. The newer nomenclature is perhaps a bit more descriptive in a quantum mechanical sense, but at least four different versions of it have been used since 1965, causing considerable confusion to the nonspecialist. Furthermore, none of the new systems is universally accepted as yet.

recognized, was quite inadequate. The separation of the superimposed absorptions was handled more properly by Grandjean and Goody (1955), who used Kuiper's data to derive a pressure-concentration product $P_s^2 C_v = 1.6 \pm 0.5 \times 10^2 \text{ mb}^2$ (P_s = surface pressure in mb, C_v = volume mixing ratio). A concentration cannot be derived from a strong band alone, unless very high resolution figures, available in 1955, Grandjean and Goody found the CO_2 concentration to be about 2% by volume. Using modern values for the pressure, the concentration calculated exceeds 100%. Considering the relatively poor resolution in these pioneering infrared spectra, the lack of good laboratory line strengths, and the fact that the theory used made no allowance for such refinements as temperature differences or the proper individual damping constants for each atmosphere, a factor-of-six error is not surprising.

In 1963, while searching for (and finding) water vapor in the Martian atmosphere, Spinrad, Münch, and Kaplan discovered on the same plate a number of faint spectral lines in the 8700 Å region which are not present in solar spectra (Kaplan et al., 1964). These proved to be lines of the very weak $5\nu_3$ band of CO_2 , a band so weak that it should not have appeared at all unless the CO_2 abundance of Mars were much higher than previously thought by astronomers. Such proved to be the case, and Kaplan, Münch, and Spinrad derived a CO_2 abundance for Mars of $50 \pm 20 \text{ m atm}^*$ assuming a 200°K Martian temperature and based upon that one plate (Kaplan et al., 1964). A detailed calibration by Owen of the same plate corrected the Kaplan, Münch, and Spinrad air-mass function and allowed for doubling back of the band, thereby resulting in a revised abundance value of $46 \pm 20 \text{ m atm}$ (Owen, 1964). Much of the large probable error arose from the uncertainty in the measurement of the one plate of Mars upon which the numerical values derived from all of the elaborate theory depended. This particular plate initiated the modern era in spectroscopic investigation of the atmosphere of Mars.

During the Mars apparitions of 1964-1965 and 1967, there were intensive efforts by many workers to determine CO_2 abundance (and surface pressure). Many additional photographic plates were taken of the $5\nu_3$ band at the highest available resolution (Spinrad et al., 1966; Owen, 1966; Barker, 1967). The primary source of error here was the limited resolution available for so weak a band and the problem of continuum location. Photoelectric scans of the $2\nu_1 + 3\nu_3$ (1.04μ) band (Belton et al., 1968) and the $\nu_1 + 2\nu_2 + 3\nu_3$ (1.05μ) band (Belton and Hunt, 1966; Belton et al., 1968; Giver et al., 1968), which are stronger and somewhat easier to measure accurately, were carried out. These bands, being stronger, are no longer on the linear part of the curve of growth (see Section 5.2), however, and are affected by pressure. Also, there is still a problem of continuum location, which tends to become even worse at longer wavelengths. Carleton et al. (1969) used a PEPSIOS Fabry-Perot interferometer to scan two lines of the $\nu_1 + 2\nu_2 + 3\nu_3$ band. This work was observationally of high accuracy, but errors in the reduction process appear to have resulted in a value approximately 10% too large.

*See Appendix A, Units Used for Atmospheric Abundances.

While visiting at the Jet Propulsion Laboratory during 1964, J. Connes and P. Connes (1966) perfected an interferometric spectrometer capable of high spectral resolution of Mars in the near infrared (1.2-2.5 μ). During the April 1967 Martian opposition, the Connes were able to obtain spectra at a resolution in excess of 0.08 cm^{-1} (Connes et al., 1969). The resolution of the strong CO_2 bands in this region was sufficiently high to attempt determination of both abundance and pressure from the strong bands. Preliminary results were given by Gray Young (1969), and an analysis fitting 15 CO_2 bands, line-by-line, using Voigt profiles (see Section 5.2) has now been completed (Gray Young, 1971a). This last result, 72.1 ± 0.5 m atm of CO_2 , must be considered the best planetwide spectroscopic analysis to date. Because this value is sufficiently more accurate as a planetwide mean than the preceding results, none of the previous results will be discussed further. Perhaps the largest remaining source of uncertainty, a potential systematic error not reflected in the quoted error, is the effective path through the atmosphere. Gray Young (1971a) used $\eta = 3.5$ (see Section 5.2), as a reasonable value for an intermediate degree of planetary limb darkening. The extreme possibilities add no more than roughly ± 3 m atm to the uncertainty. Pressure broadening by argon is only about half as effective as CO_2 self-broadening. The presence of a small amount of argon would result in a slightly smaller Lorentz half width (see Section 5.2) for Gray Young's calculations and would require a slightly larger amount of CO_2 to match the measured line equivalent widths (see Section 5.2). It is always difficult to allow properly for systematic error, but it does not appear overly conservative to suggest 95% confidence that the limits were no more than ± 5 m atm from 72 m atm during April 1967.

One reason that considerable confidence can be placed in the interferometric result is that it represents a mean over an entire hemisphere and, in fact, more than a hemisphere, since Mars rotates during the long integration time required to obtain a good interferogram. A spectrograph slit typically will project a footprint on Mars covering only about 1% of the hemisphere, although planetary rotation will considerably increase the averaged area. A spacecraft radio occultation experiment literally provides only two points, one at ingress and one at egress, and radar studies have indicated Mars to have large elevation differences (see Section 3.3). In fact, several attempts have been made both from the ground (Wells, 1969; Belton and Hunten, 1969; Wells, 1971) and from spacecraft measurements (Herr et al., 1970) to determine topography from the varying CO_2 abundance.

In 1966, Leovy (1966a, 1966b) and Leighton and Murray (1966) provided evidence that the polar caps of Mars could consist primarily of frozen CO_2 . The Mariner 7 infrared radiometer has confirmed that the temperature of the south polar cap is about 150°K, a temperature low enough to permit condensation of CO_2 (Neugebauer et al., 1969). This indicates the atmospheric CO_2 abundance must be, at least, slightly variable. The imaging experiment on Mariner 7 gave evidence that in some areas the south polar cap thickness was "at least tens of meters" rather than millimeters or centimeters (Sharp et al., 1971). However, there is no positive method to estimate the bulk density or fractional CO_2 content of the polar cap material. The CO_2 abundance quoted here, 72 m atm, appears proper for April 1967, which corresponds to mid-summer in the northern hemisphere of Mars. The abundance could vary significantly during the Martian year.

Carbon Monoxide

The discovery of CO on Mars was first reported by Kaplan, Connes, and Connes (1969) from interferometric spectra taken during the 1967 opposition. Some 50 lines of the 2-0 (2.35μ) band were identified, as well as a few unblended lines in the 3-0 (1.57μ) band. The abundance reported was 21 cm atm in the total optical path (or 5.6 cm atm in a vertical column, using the suggested $\eta = 3.75$). A line-by-line fitting of Voigt profiles to the same data by Gray Young (1971b) indicated $47 \pm_{-24}^{+32}$ cm atm in the total path. The difference is caused by a small change in continuum placement, a subjective choice, which results in a 25% difference in the measured equivalent widths of the lines. Unfortunately, on the appropriate part of the curve of growth, a 25% difference in equivalent widths is reflected as a ~200% difference in abundance. Accepting Gray Young's result as the more thorough, and applying the $\eta = 3.75$ suggested by Kaplan, Connes, and Connes (1969) as appropriate for lines in (that) "location on the curve of growth," a CO abundance of $12.5 \pm_{-6.4}^{+8.5}$ cm atm is suggested as the best available figure. This gives a CO:CO₂ mixing ratio in the bulk lower atmosphere of 1.7×10^{-3} .

Isotopes of Carbon and Oxygen

Kuiper (1964) first reported C¹²O¹⁶O¹⁸ and C¹³O¹⁶ to be present on Mars, but his spectral resolution was too poor to give accurate abundances. Kaplan, Connes, and Connes (1969) found lines of C¹³O¹⁶ and C¹²O¹⁸ in their work on the normal isotope C¹²O¹⁶. Gray Young (1971a) reported on C¹²O¹⁶O¹⁸, C¹²O¹⁶O¹⁷, and C¹³O¹⁶ in her comprehensive work on Martian CO₂. No departure from terrestrial isotopic ratios was found for C¹³ or O¹⁸. Gray Young's (1971a) O¹⁷ abundance appears large, but the band is very weak, and she does not feel that the difference from the terrestrial ratio is necessarily significant.

Water Vapor

The question of the existence of water vapor in the atmosphere of Mars is a classic one in planetary spectroscopy. Pioneer studies were carried out at Lowell and Lick Observatories, shortly after the turn of the century, and at times yielded apparently positive results, the uncertainty being due to inadequate equipment and technique. Adams and his co-workers at Mt. Wilson gave considerable attention to the problem between 1925 and 1943, at times with apparently positive results, but always with large probable errors. A review of these early efforts is given by de Vaucouleurs (1954).

The 1962-1963 apparition of Mars resulted in two independent reports of successful H₂O detection on Mars. Spinrad, Münch, and Kaplan, working at the 100-in. Mt. Wilson reflector, obtained a spectrogram of the $2\nu_1 + \nu_2 + \nu_3$ (8200-Å) water band at a dispersion of 5.6 Å/mm. It showed 11 lines with satellites at the doppler displacement appropriate to Mars, most of them

*Old calibration. New laboratory line strengths and temperature corrections indicate these values are too large by a factor of about two (Farmer, 1971a). (See Appendix A for definition of units.)

apparently free of blends with other terrestrial or solar lines (Spinrad et al., 1963). Detailed analysis indicated an abundance of $14 \pm 7 \mu^*$ of precipitable water. The analysis was based upon about one-third of the length of the image of the lines, namely, that part covering the polar region (Kaplan et al., 1964). Working with a 50-cm (20-in.) reflector at the scientific station on the 3600-m (12,000-ft) Jungfrauoch in Switzerland, Dollfus used a Lyot filter and half-wave plate to alternately isolate the 1.4μ band and two adjacent bands. He then subtracted the terrestrial component as determined from measurements of the Moon and other objects. His result was an average over the planet of 200μ of precipitable water (Dollfus, 1963). With recalibration, the value from the same observations was later reduced to 45μ (Dollfus, 1965). However, the spectrogram of Spinrad, Münch, and Kaplan marked the effective discovery of water on Mars, since it was the first widely accepted evidence of water, being based upon specific identification of spectral features isolated from telluric interference. That spectrogram also resulted in a major program to improve knowledge of water on Mars.

An intensive observing program was carried out by Schorn et al., during the 1964-1965 apparition of Mars, in an attempt to refine the previous result (Schorn et al., 1967). Over a 9-month period, 19 well-exposed spectrographic plates were obtained at McDonald and Lick Observatories, at dispersions of 4.09 and 4.14 Å/mm, respectively. Those taken from September through mid-November 1964 showed no water vapor; those taken during late December and January indicated about $15 \mu^*$ of precipitable water in the northern hemisphere only. The season was late spring in the northern hemisphere of Mars. Further measurements were impossible until May, due to insufficient doppler shift (small relative radial velocity) during the opposition period, which occurred in March. During May and June, 10 to $25 \mu^*$ of water were detected in both hemispheres; apparently more detected in the southern hemisphere than the northern. The season was early summer in the northern hemisphere of Mars.

Equipment construction and bad weather combined to prevent further water vapor observations during the 1967 Mars apparition. In 1969, good dry observing conditions combined with new equipment, allowing 2 Å/mm dispersion, yielded a large number of plates and the best results yet obtained. Even photographic reproductions of the spectrograms clearly show the Martian water lines. Schorn, Farmer, and Little (1969) found $26 \pm 5 \mu$ of water in the northern hemisphere of Mars and less than one-third of that amount in the southern hemisphere, during February and March of 1969. In a limited observing program, Owen and Mason (1969) found similar results, when corrected by Farmer's (1971a) line strengths. Tull (1970, 1971) described the latitude variation of water vapor in more detail, finding a peak abundance of about 48μ at a latitude 30° - 40° N, in late March 1969. Little (1971) presented extensive results for $110^\circ < L_s < 145^\circ$ during the 1969 opposition. Barker et al. (1970), have extended these studies through March 1970, finding water vapor increasing from undetectable ($<20 \mu$) in August 1969, to 45 - 50μ , over a wide latitude range, in March 1970. Figure 1 is adopted from Farmer (1971b), who uses most of the observations noted above to show the abundance of water vapor on Mars as

*See footnote on page 4.

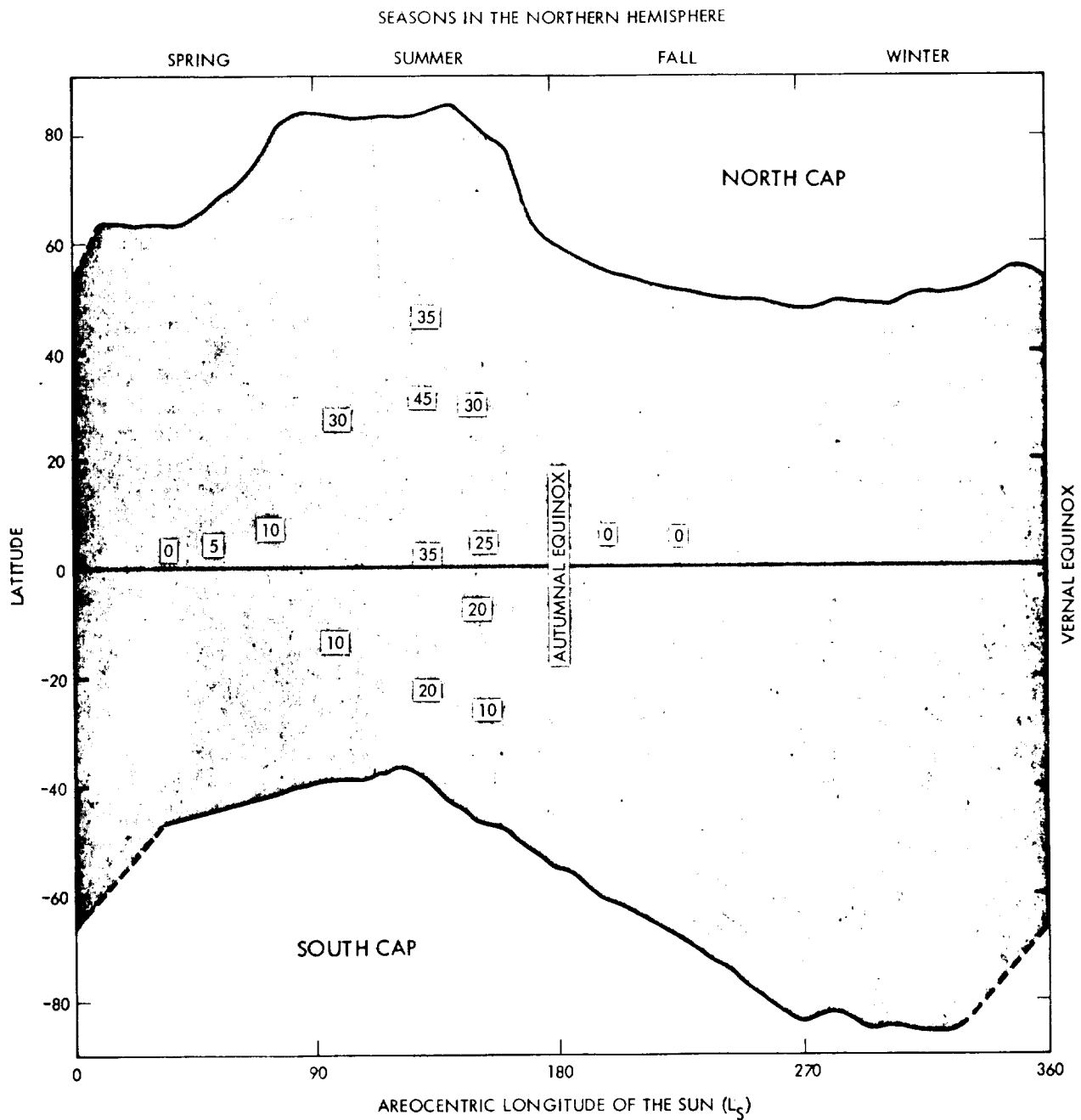


Fig. 1. Water vapor abundances (in precipitable microns). This is a plot of abundance as a function of season (the abscissa) and latitude (the ordinate). It does NOT show diurnal or longitudinal variation, functions which are still essentially unknown.

a function of location and season. All abundances shown on Fig. 1 have been derived from the original measured equivalent widths, using a common method of reduction to the vertical water content. Therefore, they should contain minimum relative errors, resulting from the choice of differing averaging factors, intrinsic strengths, and analytical techniques. The recent data derived by Barker et al. (1970), and Barker (1971) have not been added to Fig. 1, because their areographic resolution was poor (Mars had an angular diameter less than 5 arc seconds by March 1970). These data are shown separately in Fig. 2. There is some evidence for symmetry, however, with water vapor rising to a peak in the temperate latitudes of each hemisphere during the midsummer season. A highly informative account of the history of the search for water vapor on Mars was produced by Schorn (1971).

Upper Atmospheric Constituents

On July 31 and August 5, 1969, Mariners 6 and 7 flew past Mars carrying ultraviolet spectrometers sensitive to wavelengths from 1100 Å to 4300 Å. The instruments have been described by Pearce et al. (1971). Besides CO_2 and CO , the spectrometers found CO_2^+ , CO^+ , C , O , and H (Barth et al., 1971). None of these is really surprising as an upper atmosphere constituent, as they are obvious dissociation and ionization products of the three molecules known to be present in the lower atmosphere. The Lyman α resonance line of atomic hydrogen was seen to an altitude of more than 20,000 km above the Martian surface (Barth et al., 1971), which was unexpected. Hydrogen is not easily retained by a planet as small as Mars, and this would imply a considerable continuous loss of water (assuming that water is the source of the hydrogen, rather than captured solar wind protons or some other mechanism).

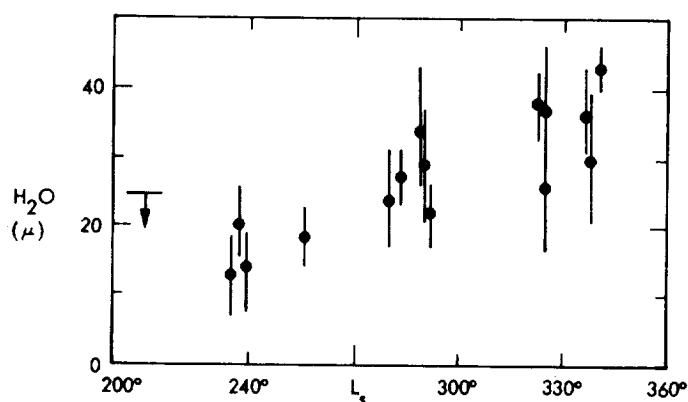


Fig. 2. Water vapor abundances (in precipitable microns). These data from Barker (1971) are for the southern hemisphere Spring-Summer season, values of L_s (areocentric longitude of the Sun) not studied until 1970.

Ozone

Theoretically, there should be at least a very small amount of ozone in the atmosphere of Mars. Belton and Hunten (1969b) calculated an abundance of about $2 \times 10^{16} \text{ cm}^{-2}$ ($7.4 \mu \text{ atm}$), assuming their oxygen detection (see molecular oxygen) to be valid. In fact, that value would seem, at best, to be an upper limit on the ozone abundance, since the tentative O_2 identification seems to have proven incorrect. Barth and Hord (1971) report the existence of an absorption feature in Mariner data over the polar regions, a feature having all the characteristics of the Hartley absorption band of O_3 . It could be explained either by $10 \mu \text{ atm}$ (3×10^{16} molecules) of O_3 in the atmosphere or by O_3 trapped in the solid CO_2 of the polar cap. It is intended that the Mariner 1971 flights make a new study of ozone on Mars (Hord, Barth, and Pearce, 1970).

5.1.2 Constituents Sometimes Assumed Present

Argon

Argon has no spectral lines in regions of the spectrum observable from the surface of the Earth, yet there has been a general assumption that some argon should be present in the atmosphere of Mars. On Earth, argon has resulted mainly from decay of potassium 40. If Mars has undergone the same process of differentiation and surface concentration as the Earth, then the argon abundance in the Martian atmosphere would be expected to be proportional to its surface area, relative to the Earth. The surface area of Mars is roughly 28% that of the Earth. Since the Earth has about 74.5 m atm of argon, Mars might be expected to have about 28 m atm. In fact, the abundance of argon is almost certainly less than 10 m atm. The total atmospheric pressure (see Section 5.2) is so near the partial pressure of CO_2 that the presence of a large amount of argon is untenable.

Molecular Nitrogen

At one time, molecular nitrogen was thought to be the major constituent of the Martian atmosphere. Like argon, N_2 has no detectable absorption features visible from the ground in its spectrum, so this was simply a guess by terrestrial analogy. As a relatively accurate surface pressure and CO_2 abundance became known, it was realized that there was no room left for any large amount of nitrogen. Nitrogen has a number of electronic bands in the ultraviolet, but none of these were detected by Mariners 6 and 7 (Barth et al., 1971). Dalgarno and McElroy (1970) have thereby set an absolute upper limit of 5% nitrogen in the Martian atmosphere and a probable upper limit of 0.5%, assuming the eddy transport coefficient is the same in the Martian atmosphere as in that of the Earth. Thus, nitrogen must be considered a minor constituent.

Molecular Oxygen

The search for molecular oxygen on Mars is second only to that for water vapor, both historically and in expended effort. The searches of Adams, Dunham, and St. John at Mt. Wilson, during the period 1926-1934, have been summarized by Dunham (1952). The results of the searches were negative. A

search by Kaplan, Münch, and Spinrad was also negative and resulted in an upper limit of 70 cm atm (Kaplan et al., 1964). Then, Belton and Huntén (1968) reported a tentative identification of 20 cm atm of O_2 on Mars. A more thorough search by Margolis, Schorn, and Gray Young (1971) has set an upper limit of 15 cm atm (assuming $\eta = 3$), however, and molecular oxygen must still be considered an undetected minor constituent of the Martian atmosphere. Since there is atomic oxygen in the upper atmosphere of Mars, there should be a small amount of molecular oxygen of photochemical origin as well, but theoretical calculations of such abundance are based on too few data to be considered reliable.

Oxides of Nitrogen

In 1960, Kiess, Karrer, and Kiess presented "A New Interpretation of Martian Phenomena," a claim that many observational results of long standing were due to the presence of the various oxides of nitrogen on Mars. That paper contained no new observational results, consisting of a rediscussion of previously observed results. Virtually every statement in the paper has since proved untenable. The paper is mentioned because it unfortunately resulted in a concern about nitrogen oxides which took a long time to dispel.

Sinton (1961), Kaplan (1961), and Huang (1961) immediately objected to Kiess, Karrer, and Kiess' work, Sinton and Kaplan on observational grounds, and Huang on theoretical grounds. In an attempt at rebuttal, Kiess, Karrer, and Kiess (1963) showed a section of microphotometer tracings of Mars and the Sun. This proved chiefly that their Martian spectrogram exhibited a very poor signal-to-noise ratio. The 1963 paper also contained a statement that 1 to 2 mm atm was sufficient NO_2 to account for many of the observed effects. Meanwhile, a new observational study by Spinrad set an upper limit of 1 mm atm for the NO_2 abundance in the Martian atmosphere (Spinrad, 1963). This was later reduced to an upper limit of 8 μ atm by Marshall (1964). Another detailed observational study by O'Leary indicated, very conservatively, that the upper limit of NO_2 abundance was no more than 0.1 mm atm (O'Leary, 1965). Still another study by Owen verified Marshall's results (Owen, 1966).

Kuiper (1964) has made spectrographic searches for N_2O (<800 μ atm) and NO (<20 cm atm). Sagan et al. (1965) set theoretical limits on NO and HNO_2 , based on observed NO_2 limits. They also set limits on N_2O_4 , based on the well-known relationship between monomer (NO_2) and dimer (N_2O_4). Beer, Norton, and Martonchik (1971) have set an observational upper limit on N_2O_4 of 500 μ atm, using an interferometric spectrometer. Thus, there is a great deal of evidence that oxides of nitrogen are, at most, insignificant components of the Martian atmosphere.

Sinton Bands

In 1957, Sinton reported the presence of three bands at 3.43 μ , 3.56 μ , and 3.67 μ (later revised to 3.45 μ , 3.58 μ , and 3.69 μ) in a spectrometer tracing of Mars, made with the 200-in. Palomar reflector. These were generally

attributed to some compound with a C-H bond, although such interpretations were far from completely satisfactory (Rea et al., 1963). Later, rather positive identification with telluric HDO was made of the $3.58\ \mu$ and $3.69\ \mu$ features (Rea et al., 1965). Recent high resolution studies with an interferometric spectrometer (Beer, Norton, and Martonchik, 1971) have shown the $3.45\ \mu$ band, the weakest of the three, to be spurious. (At least it did not appear in 1969.)

"Reduced Gases"

Connes, Connes, and Kaplan (1966) reported the discovery of unidentified absorption bands in the near infrared, which they suggested were in part, probably caused by "reduced gases, including substituted methanes." There has been no confirmation of the existence of the lines, let alone positive identification, and the observations are now generally considered invalid.

5.1.3 Upper Limits on Possible Atmospheric Constituents

It has been possible to place upper limits on the abundances of a number of relatively simple molecules which are conceivable components of the Martian atmosphere. The limits in the following table have been reported by Kuiper (1952 and 1964), who surveyed the $1\text{-}2.5\ \mu$ region with a standard spectrometer, and Beer et al. (1971), who surveyed the $2.8\text{-}4.0\ \mu$ region with an interferometric spectrometer.

<u>Molecule</u>		<u>Abundance Upper Limit</u>	<u>Reference</u>
Carbon suboxide	C_3O_2	$200\ \mu\text{-atm}$	Beer et al., 1971
Ammonia	NH_3	$1\ \text{mm-atm}$	Kuiper, 1964
Methane	CH_4	$1\ \text{mm-atm}$	Kuiper, 1964
Ethane	C_2H_6	$10\ \text{mm-atm}$	Kuiper, 1952
Ethylene	C_2H_4	$30\ \text{mm-atm}$	Kuiper, 1952
Acetylene	C_2H_2	$20\ \text{mm-atm}$	Beer et al., 1971
Hydrogen sulfide	H_2S	$30\ \text{mm-atm}$	Beer et al., 1971
Carbonyl sulfide	COS	$1.5\ \text{mm-atm}$	Beer et al., 1971
Formaldehyde	HCOH	$50\ \mu\text{-atm}$	Beer et al., 1971
Formic acid	HCOOH	$70\ \mu\text{-atm}$	Beer et al., 1971
Hydrogen chloride	HCl	$11\ \mu\text{-atm}$	Beer et al., 1971

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APPENDIX

UNITS USED FOR ATMOSPHERIC ABUNDANCES

A number of somewhat specialized units are in common use by atmospheric physicists to describe abundances. A brief glossary of some of these terms is given below, followed by derivations of the numerical relationships between some of them.

Amagat	The amagat is a dimensionless unit of density normalized to STP conditions (1 atm & 0°C). One amagat implies a number density equal to Loschmidt's number.
Meter-atm	A meter-atm of gas is that abundance which would occupy a path length of 1 m at 1 atm pressure. The temperature is often assumed (as here) to be 0°C, but this is not a part of the latest spectroscopic definition wherein the temperature must be specified. Units of cm-atm, km-atm, etc., have obvious analogous definitions.
Meter-amagat	A meter-amagat of gas is that abundance which would occupy a path length of 1 m at a density of 1 amagat.
Millibar (mb)	The millibar is a unit of pressure, of course, equal to 10^2 newtons m^{-2} or 10^3 dynes cm^{-2} . Abundances are quoted as partial pressures in many Martian papers, commonly using millibars as the pressure unit.
Torr	The torr is also a unit of pressure, being that pressure sufficient to raise a column of mercury at 0°C by one millimeter in a one standard gravity field. Abundances are sometimes quoted as partial pressures in torr.
Atmosphere (atm)	The atmosphere is still another pressure unit, derived from standard Earth atmospheric pressure, used to give abundances as partial pressures.
Grams per square centimeter	On occasion, an abundance will be given in units of the mass of a given molecule above some unit area, $g\ cm^{-2}$ being most commonly used.
Microns (H ₂ O)	Water vapor abundance is often given in terms of the thickness of the layer which would form if the vapor were "precipitated out." Sometimes the unit is given as "precipitable microns" or any other convenient unit of length.

Other measures of abundance include volume percent (or volume mixing ratio), mass percent, and number density, all of which have obvious meaning.

The numerical relationship among the pressure units is as follows:

$$\begin{aligned} 1 \text{ mb} &= 1.000 \times 10^2 \text{ newtons m}^{-2} \\ 1 \text{ torr} &= 1.333 \times 10^2 \text{ newtons m}^{-2} \\ 1 \text{ atm} &= 1.013 \times 10^5 \text{ newtons m}^{-2} \end{aligned}$$

The meter-amagat can be related to partial pressure units as follows:

$$\text{by definition } P = \frac{F}{A} = \frac{mg}{A}$$

P = pressure

F = force

A = area

m = mass

g = local acceleration of gravity

ℓ = path length

V = volume

μ = molecular mass (phys. scale)

N_o = Avogadro's number (phys. scale)

n_o = Loschmidt's number

$$\text{obviously } \frac{m}{A} = \frac{m\ell}{V}$$

Path length in m-amagat units refers to STP conditions. Therefore, under standard conditions of temperature and pressure

$$\left(\frac{m}{V}\right)_{\text{STP}} = \frac{\mu}{N_o} n_o$$

and

$$P = \frac{n_o}{N_o} \mu \ell g = 4.4601 \times 10^{-2} \mu g \ell_{\text{m-amagat}} \text{ in mKs units}$$

For Mars specifically, $g = 3.71 \text{ ms}^{-2}$ and:

$$P (\text{newtons m}^{-2}) = 0.1655 \mu \ell_{\text{m-amagat}}$$

or

$$P (\text{mb}) = 1.655 \times 10^{-3} \mu \ell_{\text{m-amagat}}$$

The mass per unit area M is equal to local pressure divided by local surface gravity. Its expression in terms of m-amagats can be taken directly from above

$$M (\text{kg m}^{-2}) = 4.4601 \times 10^{-2} \mu \ell_{\text{m-amagat}}$$

In various partial pressure units the relationship becomes

$$M \text{ (g cm}^{-2}\text{)} = 10^3 \frac{P \text{ (mb)}}{g \text{ (cm s}^{-2}\text{)}}$$

or

$$M \text{ (kg m}^{-2}\text{)} = \frac{P \text{ (newtons m}^{-2}\text{)}}{g \text{ (m s}^{-2}\text{)}}$$

Precipitable water units W can be converted from microns to mass per unit area simply by multiplying by the density of water (1 g cm^{-3}). Thus, 1 micron of water equals $10^{-4} \text{ g cm}^{-2}$ or $10^{-3} \text{ kg m}^{-2}$. Converting to equivalent path units

$$W \text{ (microns)} = 8.028 \times 10^2 \ell_{\text{m-amagat}}$$

In partial pressure units (using $g = 371 \text{ cm s}^{-2}$)

$$W \text{ (microns)} = 2.695 \times 10^4 P \text{ (mb)}$$

5.2 SURFACE PRESSURE

DATA SUMMARY

The mean surface pressure of Mars is 5.2 ± 1.0 mb, exclusive of seasonal variations. It is considered unlikely that seasonal variations can exceed ± 1.5 mb, and they are probably much smaller. Pressures at the extreme high and low elevations may reach 2.3 mb (+10 km) and 11.5 mb (-10 km), respectively, which is of greater significance.

DISCUSSION

5.2.1 Historical (Photometric and Polarimetric Surface Pressures)

The history of the study of Martian surface pressure is an excellent example of the way science often progresses; an apparent convergence toward an answer, followed by one or more quantum jumps to completely different answers as systematic errors are isolated, and then a new convergence (hopefully toward the final answer).

Within the past half century, Donald H. Menzel (1926), using photometric data, established an upper limit of 50 torr (66 mb) for Martian surface pressure. He noted that if the atmosphere contributed only 2% of the planetary albedo, the surface pressure would be 20 torr (26 mb). In 1929, Lyot (1964), reporting upon polarimetric observations, suggested that the surface pressure must be less than 18 mm (24 mb). These pioneering efforts were followed by many other photometric and polarimetric studies, and de Vaucouleurs (1954) concluded, in summary, that the surface pressure must be 64 ± 3 torr (85 ± 4 mb).

All the "classical" attempts to determine the Martian surface pressure involved unverifiable assumptions. Each successive worker pointed out the "unwarrantable assumptions" of his predecessors and proceeded to make a new set of his own. It is difficult to fault the work of Menzel or Lyot, who very clearly stated their assumptions and qualified their conclusions, but many later workers were distinctly overconfident in their assignment of probable errors. A detailed critique of these surface pressure measurements was presented by Chamberlain and Hunten (1965). Their criticisms are summarized in the following paragraphs.

In even the best polarimetric work done to date, it was assumed

- 1) that surface polarization variation across the disk is wavelength independent.
- 2) that the phase-angle and zenith-distance vary independently with surface brightness.
- 3) that the atmosphere is a pure Rayleigh scatterer (least-reliable assumption).

Further, the conversion from intensity to surface pressure involves the absolute planetary surface brightness and atmospheric composition. Finally, the observations themselves are difficult and involve some error, even with the best of equipment and observers. According to Chamberlain and Hunten, the total error, excepting the composition effect and non-Rayleigh component effect, could be at least $\pm 50\%$.

The composition effect enters in the conversion of a derived atmospheric scattering intensity to the number of molecules or pressure. A pure CO_2 atmosphere has half as many molecules and about 75% of the surface pressure of an N_2 atmosphere with an identical scattering intensity.

If there is a non-Rayleigh component to any atmosphere, its effect depends upon the size and type of particles involved. If they are very small particles, such as typical haze or fog-type particles (a few wavelengths of light or less), the gas pressure will be overestimated by either polarimetric or photometric techniques, which assume pure Rayleigh scattering for the atmosphere. Large particles, such as ice crystals, would add a component of negative polarization at small phase angles which would conversely cause an underestimate of surface pressure. Such effects could be quite gross, causing errors of several hundred percent. In fact, a considerable amount of submicron material would simply invalidate the whole approach (photometry has shown that there is at least some non-Rayleigh component).

The photometric approach usually contains its own assumptions, such as ignoring illumination of the ground by the atmosphere, illumination of the atmosphere by the ground, and absorption. Even if these assumptions are allowed, it is impossible to correct for the non-Rayleigh scattering component known to exist.

Photometry and polarimetry remain valid methods of studying the surface of Mars, and perhaps with accurate knowledge of the atmosphere gained from other methods, they may provide useful results on the non-Rayleigh component of the Martian atmosphere. However, photometry and polarimetry, by themselves, are not capable of establishing a useful surface pressure for the planet.

5.2.2 Spectroscopic Surface Pressures

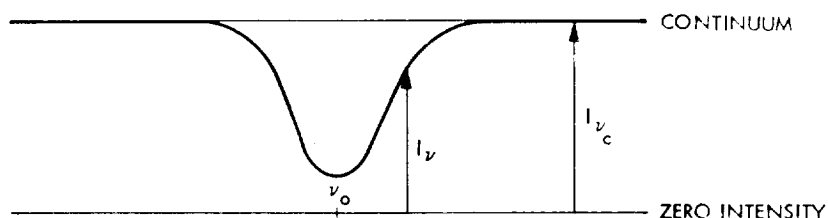
Theory and Techniques

Astronomical molecular spectroscopy is an active and complex field of research which cannot be easily summarized in a few pages. The following paragraphs are intended to acquaint readers without an astrophysical background, with some of the basic concepts and terminology of this field.

An astronomical spectrogram is a photograph of a light source which has been instrumentally dispersed (spread out) in wavelength, usually by means of a diffraction grating or, occasionally, a prism. In planetary spectroscopy the source is usually sunlight reflected from a planet, and the instrument is usually one of several types of large spectrographs, although recently Michelson interferometers have been used to produce spectra in so-called Fourier spectroscopy (see page 5).

In an astronomical spectrogram of the planets, the reflected continuum of light will normally exhibit certain, relatively discrete, portions weakened relative to adjacent parts of the spectrogram. These weakened wavelengths, or absorption features, correspond to the natural absorbing frequencies of atoms or molecules between the source (Sun) and the detector (spectrometer). In the spectra of Mars, the absorbers may be on the Sun itself (Fraunhofer lines), in the atmosphere of Mars, or in the Earth's atmosphere. The major Martian absorber, CO_2 , is not present on the Sun; therefore, solar interference with absorption lines at that frequency would be random and due to something other than CO_2 . Also, by means of the Doppler effect (identical frequencies, on different bodies, shift slightly with respect to each other if the bodies have any relative radial velocity), absorptions at the same wavelength can be separated by making observations at a time of large radial velocity. This effect is used particularly to separate lines of the same gas appearing on more than one body, such as water vapor on Earth and Mars.

If a microdensitometer tracing is made of a single absorption line on a photographic plate and the image densities are converted to intensities, the results may be somewhat bell-shaped and usually will be fairly symmetrical, as shown below. Similar displays can be made on a strip chart recorder,*



if photoelectric detection is used, scanning through the spectrum on a step by step basis. Assuming the continuum intensity to be essentially constant and unabsorbed over the interval of integration, the total absorption A in the line (the shaded area) can then be expressed as

$$A = \int_{-\infty}^{\infty} \left(I_{\nu_c} - I_{\nu} \right) d\nu = I_{\nu_c} \int_{-\infty}^{\infty} \left(1 - \frac{I_{\nu}}{I_{\nu_c}} \right) d\nu$$

where ν is the frequency, I_{ν} the intensity at ν , and I_{ν_c} the continuum intensity. In practice, the integration (measurement) is not carried to infinity but rather is terminated when the difference $I_{\nu_c} - I_{\nu}$ cannot be separated from the noise (unless a mathematical model for I_{ν_c} is used). The effect of finite instrument resolution (instrument profile) is a complication which will not be discussed here, except to note that it causes line shapes to spread, but usually leaves total absorption unaltered (although it may cause nearby lines to make that absorption difficult or impossible to measure).

*In actual practice, microdensitometer or spectrometer data may be transferred onto magnetic tapes for computer processing.

Total absorption is generally expressed in terms of equivalent width W , the width of an equivalent rectangular line of zero intensity everywhere within the line. In other words, $A = I_{\nu_c} W$, and

$$W = \int_{-\infty}^{\infty} \left(1 - \frac{I_{\nu}}{I_{\nu_c}} \right) d\nu$$

The relationship between equivalent width W of a given spectral line and the product of the number of molecules of absorbing gas (in the column creating the spectral line) times the intrinsic strength of the line is called the curve of growth. When that product is small (the weak line region) the relationship is a linear one, and doubling the number of molecules doubles the equivalent width. When the product becomes larger and the line begins to saturate, there is a transition to a square root law (the strong line region), requiring four times as many molecules to double the equivalent width. In the transition and strong line regions, the gas density also enters the relationship. In a real atmosphere, the number of molecules cannot be changed, but molecular absorption bands or lines of different intrinsic strengths can be utilized, determining an abundance with lines of a very weak band and density-abundance product with a strong band, thus allowing derivation of atmospheric pressure. The Curtis-Godson approximation allows ready comparison between a real atmosphere (with temperature and pressure decreasing with height) and a fictitious homogeneous atmosphere (for details, see Chap. 6, Goody, 1964). In fact, the pressure determined spectroscopically, assuming a homogeneous atmosphere, is very nearly half the surface pressure in the real atmosphere. This is the technique that was used in the first and most of the successive spectroscopic pressure determinations (Kaplan, Münch, and Spinrad, 1964).

The detailed shape of a spectral line is usually the result of combined effects of Doppler (thermal) broadening and pressure (collisional) broadening, referred to as a Voigt profile. The integral describing the area under such a profile is a function of two parameters, usually identified as the Voigt function (also referred to as the Hjerting function). Numerical tabulations have been produced by Hummer (1965), among others. The relative contributions of Doppler and pressure broadening to a Voigt profile are a function of temperature, pressure, and line strength.

Rotational temperature can be derived by comparing the relative intensities of lines in a given rotation-vibration band (e.g., Gray, 1969). Then for an assumed abundance and pressure, Voigt profiles can be used to calculate precise equivalent widths for each line in many different bands. These calculated widths are then compared with measured equivalent widths, and the process is iterated until the residuals reach a minimum. Using this process, it is not necessary that bands of any particular strength be used, but a greater number of bands and a wider range of strengths provide a more accurate solution.

Observing techniques have improved considerably in recent years. Initial work on the Martian surface pressure was carried out with a standard high dispersion coude spectrograph, using photographic detection. Such instruments have been described in detail by Bowen (1962). Photoelectric detection has often been used on the 1.04, 1.05, and 1.06 μ bands to improve detective quantum efficiency and permit acquisition of spectra of adequate resolution in a reasonable observing period. All conventional spectrographs necessarily have an entrance slit which accepts only a small fraction of the light from a planetary image. In the infrared bands where the flux is low, the limited amount of light available results in poor resolution. The development of the Fourier spectrometer by P. Connes (Connes and Connes, 1966) has made it possible to accept the total flux from a planet and, further, to record virtually all wavelengths simultaneously (to multiplex), even in infrared regions where photographic plates are unavailable. This significantly improves the resolution of the infrared bands and provides far more accurate data. The latest spectroscopic results are based largely upon Fourier spectroscopy. An excellent elementary discussion of Fourier Spectroscopy has been written by Beer (1968).

Observational Results

Following the initial 1963 application of spectroscopy to the determination of the surface pressure of Mars by Kaplan, Münch, and Spinrad (1964), a major effort was conducted by many observers to improve the accuracy of the results, partly because an accurate surface pressure was critical for the design of spacecraft to be landed on the Martian surface. These results appeared in a long series of papers in the "Astrophysical Journal," "Icarus," and the "Journal of Quantitative Spectroscopy and Radiative Transfer" between 1966 and 1969. Some details of this work have been given in Section 5.1, under Carbon Dioxide.

The definitive spectroscopic surface pressure is the result of Gray Young (1971), using Fourier spectra taken by the Connes during April 1967, which exhibited resolution in excess of 0.08 cm^{-1} between 1.2 and 2.5 μ (Connes et al., 1969). This resolution was sufficient to allow Gray Young to use the technique of iterative fitting of Voigt profiles described in previous paragraphs. Gray Young was able to fit 15 separate bands varying in intrinsic strength by more than three orders of magnitude, and most bands having 50 or more unblended lines, with a result of $5.16 \pm 0.64 \text{ mb}$. This quoted error does not include several potential sources of a small amount of systematic error. There is a small dependence upon composition, and the result given assumes a pure CO_2 atmosphere. Pressure broadening by argon is only about half as effective as CO_2 self-broadening. The presence of a small amount of argon would result in a slightly smaller half-width for Gray Young's calculations and would require a relatively larger amount of CO_2 to match the measured line equivalent widths. This would change the pressure slightly. Gray Young used an effective atmospheric path of 3.5, which appears reasonable for an intermediate degree of limb darkening. A longer path would imply a smaller pressure and vice versa, but at most, the potential error is only a few tenths of a millibar.

One reason that considerable confidence can be placed in the interferometric result is that it represents a mean over an entire hemisphere, and in fact, more than a hemisphere, as Mars rotates during the long integration time required to obtain a good interferogram. A spectrograph slit typically will project a footprint on Mars covering only about 1% of the hemisphere, although planetary rotation will considerably increase the averaged area. Gray Young's value can be considered a good mean surface pressure for Mars during April 1967. This seasonal qualification is necessary, since there is clearly a change in the total amount of the Martian atmosphere as the polar caps increase and decrease in size.

Belton and Hunten (1969), and Wells (1969), attempted to derive local elevations from photoelectric observations of variations in the strength of the $1.05 \mu \text{CO}_2$ band across the Martian disk. Actual pressures were not reported. The elevation trends were generally in accordance with radar and spacecraft results, but the absolute values were not reliable.

Herr et al. (1970), used the Mariner VI and VII infrared spectrometer data on the $2 \mu \text{CO}_2$ bands to make 114 pressure (and altitude) measurements which averaged 5.3 ± 0.3 mb. Individual values varied from 3.7 to 8.1 mb and the correlation with other topographic data is good. The large number and localized nature of these measurements makes them extremely valuable topographically and generally useful for mean surface pressure.

5.2.3 Occultation Surface Pressures

Theory and Techniques

When an electromagnetic wave passes through a planetary atmosphere, its amplitude, phase, and direction are changed. The ability to measure and interpret these changes depends greatly on the frequency involved. Unfortunately, there has never been an accurate observation of the optical occultation of a relatively bright star by Mars; although such observations have been made for Venus, Jupiter, Neptune, and Io. A successful occultation experiment at microwave frequencies (2300 MHz) was first carried out by Kliore, Cain, Levy, Eshleman, Fjeldbo, and Drake using the communication system of the Mariner IV spacecraft (Kliore et al., 1965).

In a modern phase-coherent communication system with the frequency reference on Earth, extremely precise measurements of phase changes can be made, although direction and precise power loss are much more difficult to determine. The integrated refractive index along the path followed by a signal transmitted from a spacecraft through a planetary atmosphere, is a direct function of the measured phase change (Kliore and Tito, 1967). The actual refractive index profile, as a function of altitude, can be determined if the atmosphere is assumed spherically symmetric, and the index is small enough to ignore bending of the ray (Fjeldbo and Eshleman, 1965). As the atmosphere penetrated by the signal becomes denser, the refractive index increases, bending of the ray increases, and knowledge of the spacecraft trajectory is necessary to correct for the effective increase in atmospheric path (Fjeldbo and Eshleman, 1965). If the atmosphere is nonspherical, the refractive index profile can still

be determined if the shape of the planet's atmosphere is known, as well as the trajectory of the transmitting spacecraft with respect to that atmosphere.

The refractive index profile is a function of the electron density and the neutral particle density. If the ionosphere is separated in altitude from the bulk of the neutral atmosphere, accuracy is improved. In an ideal experiment, at least two frequencies will be transmitted, since the refractive index of the neutral atmosphere is virtually independent of frequency, while that of the ionosphere varies inversely as the square of the frequency (Fjeldbo and Eshleman, 1965).

Assuming ionospheric effects have been removed, the refractive index profile of the neutral atmosphere is available to attempt fits with density profiles or the equivalent. (In most literature, reference is made to refractivity, which is just the refractive index minus one.) Assuming a pure CO₂ atmosphere (mass), density can be calculated directly from refractivity, and pressure and temperature are derived from the perfect gas law and the equation of hydrostatic equilibrium. This has proven quite satisfactory for Mars.

For more complex multi-component atmospheres, the data reduction cannot result in unique answers without additional assumptions or knowledge. Typically, ratios of temperature to mean molecular weight may be derivable for at least part of such an atmosphere. The more that is known about an atmosphere from other studies, the more useful the occultation technique becomes in precisely defining an atmosphere, since the quantities actually measured are measured with great precision.

Observational Results

It is now known that the Martian atmosphere is almost entirely CO₂ with at most a few percent of argon or nitrogen (see Section 5.1). As a result, occultation experiment refractivities can be converted into atmospheric variables of state with great accuracy. Mariners IV, VI, and VII have each provided two surface pressures, obtained during ingress and egress of the occulted signal. For Mariner IV, the ingress data is somewhat the better, since the uplink frequency reference transmitted from Earth remained until the signal was lost. The egress data had only the internal spacecraft frequency standard for reference until phase lock with the Earth equipment was reacquired, which occurred about 7.5 seconds after "reappearance." On Mariners VI and VII, independent local oscillators furnished frequency reference.

The pressure results obtained by the three Mariner flights are contained in Table 1. The primary references for Mariner IV are Kliore, Cain, and Levy (1967) and Fjeldbo and Eshleman (1968). Kliore, Fjeldbo, and Seidel (1970) produced detailed results on Mariners VI and VII, following a preliminary report by these authors and Rasool (1969). These six data differ presumably, because of physical differences in local elevation, since occultation results are referenced to a point on the planetary surface.

Table 1. Occultation surface pressures

Quantity	Mariner IV		Mariner VI		Mariner VII	
	Ingress	Egress	Ingress	Egress	Ingress	Egress
Location	Between Electris and Mare Chronium	Mare Acridium	Sinus Meridiani	North of Boreosyrtris	Hellasplatus	Border of Amazonis and Arcadia
Longitude (deg)	137°E	326°E	355°E	84°E	30°E	211°E
Latitude (deg)	50°S	60°N	4°N	79°N	58°S	38°N
Pressure (mb)	4.5 ± 0.8	8 ± 1.5	5.0 ± 0.5	6.2 ± 0.5	4.2 ± 0.5	7.3 ± 0.5
Martian time	July 15, 1965 5 ^h 41 ^m UT	July 15, 1965 11 ^h 25 ^m UT	July 31, 1969 5 ^h 35 ^m UT	July 31, 1969 5 ^h 44 ^m UT	Aug 5, 1969 5 ^h 14 ^m UT	Aug 5, 1969 5 ^h 44 ^m UT

5.2.4 Conclusions About Mean Surface Pressure

All photometric and polarimetric surface pressures are considered worthless, as noted earlier. Most of the individual spectrographic studies made from 1966 through 1969 were of good quality, but cannot be compared with the latest results. The Fourier spectrometer offers the best Earth-based results for mean surface pressure, since it has both high spectral resolution, in the region of the strong (infrared) CO₂ bands, and large scale spatial coverage. The spacecraft spectrometers on Mariners VI and VII produced excellent results on localized spots, but these results were based upon relatively low spectral resolution and are not as accurate for the mean as those obtained with the Fourier spectrometer. The occultation results are individually the most accurate of all, but they refer to six highly localized areas on Mars. It is suggested at this time that a mean surface pressure of 5.2 mb be used. The total probable error, including systematic effects, should be no more than ±1.0 mb, except for possible seasonal variations.

Most spectrographic measurements of CO₂ on Mars have been made during the Martian Spring and Summer, in the northern hemisphere, since these have been the seasons on Mars during opposition with Earth in recent years. The Gray Young measurement refers to midsummer, while the Mariner IR Spectrometer results were taken in late-summer. The conventional spectrographic measurements made from 1965 through 1969 used such a diverse range of equipment and assumptions, that the somewhat higher surface pressures derived cannot be considered significant. It would take a careful uniform reanalysis of all the original data to even hope to derive a significant season-pressure correlation.

Since the Martian atmosphere is now known to be composed largely of CO₂, the early CO₂ abundance figures appear directly applicable to pressure-determinations. These are probably more reliable than the early pressures themselves, because the early infrared strong band data was generally of very low resolution. With only one exception, the early abundances vary by no more

than $\pm 25\%$ from the best current value. Most of these studies average data obtained across 2- to 6-month periods of observation, thereby inhibiting any search for specific seasonal effect. Seasonal effects on the 5.2 mb mean surface pressure should not be considered to exceed ± 1.5 mb. In fact, there is no clear evidence for any seasonal effect on pressure, except for the obvious growth and shrinkage of the polar caps.

The pressure differences between high and low Martian topography at any given time would therefore far exceed any seasonal variation in the mean pressure, since a topographical difference of +10 to -10 km corresponds to 2.3 and 11.5 mb, respectively.

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SECTION 5.3

LOWER ATMOSPHERE

This section has not been revised, although it contains outdated information written almost 5 years ago. However, the improved information on the Martian atmosphere obtained over the past 5 years is so substantial that a major research effort is required to evaluate and document this data properly.

The level of sophistication now possible in producing models from this later data should provide extremely meaningful information in the near future.

The material contained in this section can be utilized as background information.

Until the later data has been documented, reference to the Viking 75 Project, Mars Engineering Model (M75-125-1) will provide the reader with improved information.

5.3 LOWER ATMOSPHERE

DATA SUMMARY

Nine models have been calculated for the lower atmosphere of Mars, each model giving atmospheric profiles for 10 different ground air temperatures. All use contemporary interpretations of the Mariner IV flight occultation data plus the best results of Earth-based observations.^{1*} The three models listed below are presented here, representing a reasonable range of ground air temperatures (180 through 290°K) for three combinations of surface pressure and composition; other models are available from the author. At this time Model I is recommended. For instructions on use of the models, see Fig. 1.

	<u>Surface pressure</u>	<u>Composition</u>
Model I (Figs. 2 through 4)	10 mb	80% CO ₂ , 10% Ar, 10% N ₂
Model II (Figs. 5 through 7)	10 mb	60% CO ₂ , 20% Ar, 20% N ₂
Model III (Figs. 8 through 10)	15 mb	60% CO ₂ , 20% Ar, 20% N ₂

DISCUSSION

Layers of the Lower Atmosphere

Using terrestrial nomenclature for classifying various regions of the atmosphere, the troposphere is the lowest region, where the source of heating is conduction from the ground and absorption of infrared energy radiated by the ground, and the principal transport of energy is by convection. It is a region where the kinetic temperature therefore decreases at a rate approximating the adiabatic lapse rate.

At some abrupt level in the lower atmosphere, the convective transport of energy virtually ceases. This level at which radiative equilibrium becomes a good first approximation is known as the tropopause. The height of the tropopause is a function of latitude, season, time of day, and solar activity. Above the tropopause the atmosphere is approximately in a state of radiative equilibrium and is called the stratosphere, a region where the temperature gradient can be either positive or negative depending upon the local conditions of the atmosphere (Goody, 1964). The numerical value of the temperature gradient will depend upon latitude, season, time of day, and solar activity.

*See page 21 for list of cross references.

Above the stratosphere but below the thermosphere is a region called the mesosphere, where the temperature in the terrestrial case decreases with increasing height. The amount of information available about the Earth's mesosphere is very limited and has been obtained largely by the observation of meteor trails through the region and from rocket data. The rocket data indicate that very large wind speeds occur with magnitudes as great as 150 m sec^{-1} (Fleagle and Businger, 1963).

Physics of the Lower Atmosphere

The important physical processes which are believed to occur in the lower atmosphere of Mars are based upon the theories of convective and radiative equilibrium plus the results of the Mariner IV occultation experiment and various Earth-based telescopic observations. These processes form the basis of Lower Atmosphere Models I, II, and III presented in Figs. 2 through 10.

Troposphere²

Mars is believed to have a normal troposphere, at least during daylight hours, with convection the dominant process for transporting energy. With this assumption, the temperature lapse rate is the dry-adiabatic lapse rate for the given composition of the atmosphere. For a well mixed atmosphere (the result of convection turbulence) the composition will be uniform with height; that is, for the mass density ρ_i of constituent i and the total mass density $\rho = \sum_i \rho_i$, we have $\rho_i/\rho = \text{constant}$. In an atmosphere of constant composition, the dry-adiabatic lapse rate is

$$A = g_0 / \langle c_p \rangle \quad (1)$$

where g_0 is the acceleration due to gravity and $\langle c_p \rangle$ is the mean value of the specific heat at constant pressure. The height of the tropopause (top of the troposphere) is below 10 km for Models I, II, and III; hence, g_0 was treated as a constant (376 cm sec^{-2}). $\langle c_p \rangle$ is given by

$$\langle c_p \rangle = \frac{\sum_i \rho_i (c_p)_i}{\sum_i \rho_i} \quad (2)$$

Specific heat for N_2 or Ar is nearly independent of temperature over the range of temperatures in question, while the value for CO_2 varies approximately as a weak linear function of temperature. Values of c_p for Ar, N_2 , and CO_2 were taken from Hilsenrath et al. (1960). Thus, the lapse rate depends both on the composition and the air temperature found in the troposphere.

The kinetic temperature of the troposphere decreases almost linearly with height since A changes only very slowly.

$$T = T_0 - Ah \quad (3)$$

where T_0 is the ground air temperature and h the height above ground. Assuming hydrostatic equilibrium and the ideal equation of state, the pressure profile for the troposphere is

$$P = P_0 \left(\frac{T}{T_0} \right)^{\mu g_0 / kA} \quad (4)$$

where P_0 is the surface pressure in dyne cm^{-2} , μ is the mean mass per molecule in gm (mean molecular mass/Avogadro's number), and k is the Boltzmann constant. The total number of atoms and molecules in the troposphere is

$$n = \frac{P}{kT} \quad (5)$$

To obtain the partial concentrations $[\text{CO}_2]$, $[\text{Ar}]$, and $[\text{N}_2]$, n is multiplied by the fractional abundance of the constituent; that is

$$[\text{CO}_2] = xn \quad (6)$$

$$[\text{Ar}] = yn \quad (7)$$

$$[\text{N}_2] = zn \quad (8)$$

where $x + y + z = 1$.

Anderson (1965) assumes that the altitude of the tropopause varies linearly with the ground air temperature, and this assumption is adopted here.

$$h_t = a(T_0 + b) \quad (9)$$

where h_t is the altitude of the tropopause and a and b are constants to be determined. The constants a and b were fitted to the results of the Mariner IV data and Model I (44% CO_2 , 10-mb surface pressure) of Prabhakara and Hogan (1965).

Anderson interpreted the Mariner IV data (immersion) to indicate a very shallow troposphere or none at all. From his interpretation he derived the result that at $T_0 = 175^\circ\text{K}$ we have $h_t = 0$. To determine the other constant in Eq. (9), Model I of Prabhakara and Hogan was used, and the model gives the result that at $T_0 = 230^\circ\text{K}$ we have $h_t = 3 \text{ km}$; hence, $a = 3/55$ and $b = -175$ for $T_0 \geq 175^\circ\text{K}$. Models will be added later for $T < 175^\circ\text{K}$ based upon straight radiative equilibrium calculations.

Stratosphere and Mesosphere

In the Martian stratosphere, radiative transport is believed to be the dominant mechanism of energy transfer. The results from the Mariner IV experiment do not indicate that radiative transport is the only mechanism present in the Martian stratosphere, but at the level of complexity justified by present knowledge of Mars, this is the only process worth consideration here.

The results of the radiative equilibrium calculations of Prabhakara and Hogan (1965) show temperature gradients which are all negative and range in magnitude from 0.9 to 1.2°K km⁻¹. Models I, II, and III (Figs. 2 through 10) have negative temperature gradients above the tropopause, and the range in magnitudes for the gradients is from 0.08 to 1.8°K km⁻¹. The radiative temperature gradients α in °K km⁻¹ are calculated from the expression

$$\alpha = \frac{T_o - 175}{62.5} \quad (10)$$

where T_o , as before, is ground air temperature. Equation (10) is derived from Figure 2 of Anderson (1965). The temperature profile from h_t to 50 km is

$$T = T_1 - \alpha(h - h_t) \quad (11)$$

where $T_1 = T(h_t)$, that is, the kinetic temperature at the height of the tropopause. From the equation of hydrostatic equilibrium and the ideal equation of state, the pressure profile from h_t to 50 km is

$$P = P_1 \left(\frac{T}{T_1} \right)^{\mu g_1 / k \alpha} \quad (12)$$

where $P_1 \equiv P(h_t)$ and g_1 is treated as a constant with the value of 370 cm sec⁻² in this region of the atmosphere. The total density profile in the stratosphere is given by Eq. (5), and the partial concentrations of [CO₂], [Ar], and [N₂] are given by Eqs. (6), (7), and (8).

The Martian mesosphere, which is thought to be a layer approximately 40 km thick, in this model is a region where the temperature decreases linearly with height to an altitude of 75 km; above 75 km to an altitude of 90 km the temperature has the constant value of 155°K, which is consistent with the data presented by Gierasch and Goody (1967), and Prabhakara and Hogan (1965). The mesospheric temperature profile used in Models I, II, and III is

$$T = \begin{cases} T_2 - \beta(h - 50) & \text{for } 50 \text{ km} < h < 75 \text{ km} \\ T_3 = 155^\circ\text{K} & \text{for } 75 \text{ km} \leq h \leq 90 \text{ km} \end{cases} \quad (13)$$

where $T_2 = 175^\circ\text{K}$ and $\beta = 0.8^\circ\text{K km}^{-1}$. The value of T_2 is fitted to the results of Anderson (1965) at an altitude of 50 km, and the value of the temperature gradient β is chosen to represent a mean value in the 50- to 75-km region. From the equation of hydrostatic equilibrium and the ideal equation of state, the pressure profile in the mesosphere is

$$P = \begin{cases} P_2 \left(\frac{T}{T_2} \right)^{\mu g_2 / k \beta} & \text{for } 50 \text{ km} < h < 75 \text{ km} \\ P_3 \exp \left[- \frac{\mu g_3}{k T_3} (h - 75) \right] & \text{for } 75 \text{ km} \leq h \leq 90 \text{ km} \end{cases} \quad (14)$$

where $P_2 \equiv P(h = 50 \text{ km})$ and g_2 is treated as a constant with the value of 362 cm sec^{-2} in the region of 50 to 75 km. P_3 is the pressure at an altitude of 75 km, and g_3 is treated as a constant with a value of 358 cm sec^{-2} in this part of the atmosphere. The total number density n is calculated from Eq. (5). The partial concentrations of the atoms and molecules are determined from Eqs. (6), (7), and (8).

Contemporary Models of the Lower Atmosphere

Types of Models

Interpretation of the data from observational and theoretical studies has produced three distinct types of models for the lower atmosphere of Mars (Fig. 11). These can be classified by the dominant process which transports the energy as convective, radiative, or convective-radiative. The "correct" choice among them is not clear; hence, we have used a combination of the convective and radiative models to produce a series of new models which are classified convective-radiative to represent the "best" approximation to the lower atmosphere of Mars.

Convective. A model which can be classified as convective for the lower Martian atmosphere has been presented by Neubauer (1966). He gives a detailed calculation for the development of thermal convection and then explores the possibilities of the influence of this process in producing "dust-devils" on Mars. In his treatment, thermal convection in the lower atmosphere of Mars is approximated by Brunt's equation

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial Z} \left[K \left(\frac{\partial T}{\partial Z} + \Gamma \right) \right] \quad (15)$$

where T is the temperature, t is the time, Z is the altitude, K is the coefficient of turbulent heat transfer, and Γ is the adiabatic lapse rate. K depends on the time of day, the Richardson number, the season, solar activity, the latitude, and altitude. Neubauer assumes K to be a function of Z only and assumes the values of K for the Earth's atmosphere to be applicable to the Martian atmosphere. To extrapolate K from the Earth's atmosphere to the Martian atmosphere without considering the seasonal, latitudinal, and diurnal variations of K for the terrestrial case is a dubious exercise. The main result of Neubauer's work is a demonstration that dust-devil formation can occur more easily on Mars than on Earth.³

A by-product of Neubauer's study is the diurnal variation of the surface temperature of Mars for southern hemisphere summer solstice at midlatitudes.⁴ Figure 3 of Neubauer shows the diurnal variation of two temperature profiles, one for the mean surface and one for 50 cm above the mean surface of Mars. Two results are readily apparent: (1) the diurnal temperature wave becomes damped very rapidly with altitude, and (2) the diurnal temperature waves for the ground and for 50 cm above the ground are in phase with each other. The first observation is disputed by the results of other authors (Leovy, 1966; Goody and Belton, 1967). The validity of the second observation needs to be established with more certainty.

Radiative. A model which can be classified as radiative is presented by Gierasch and Goody (1967). They calculate a "simple" solution to the equation describing the state of radiative equilibrium in the Martian atmosphere. From their solution Gierasch and Goody discuss and evaluate the relative importances of doppler broadening, the effect of water vapor in the Martian atmosphere, solar heating, vibrational relaxation of CO_2 , and the development of a convective troposphere. They do not present a complete model for the lower atmosphere of Mars, only the temperature profile up to an altitude of 60 km. The temperature profile was calculated for a pure CO_2 atmosphere with a surface pressure of 4.9 mb and a surface gravity of 372 cm sec^{-2} . A complete model (temperature, pressure, and number density profiles) can be calculated by using their temperature profile together with the equation of hydrostatic equilibrium and the ideal equation of state.

Convective-Radiative. The models of Prabhakara and Hogan (1965) and Leovy (1966) can be classified as convective-radiative models. Prabhakara and Hogan present a detailed calculation of the thermal structure for the atmosphere of Mars based on the absorption of solar photons in the ultraviolet and visible regions of the spectrum by O_2 and O_3 and the absorption of infrared radiation by CO_2 .⁵ Prabhakara and Hogan use an iterative procedure to calculate the atmospheric parameters of their model. When the surface pressure, surface air temperature, and atmospheric composition are specified, a first guess for the vertical temperature distribution will yield a pressure and number density distribution through the use of the equation of hydrostatic equilibrium and the ideal equation of state. From the vertical variation of the atmospheric constituents, the opacity can be determined for any level of the atmosphere. With the use of the radiative transfer equation plus the atmospheric parameters just determined, a new temperature profile is generated. With this new temperature distribution, they calculate new pressure and number density distributions and then a new opacity. Then another temperature profile is determined with the

use of the radiative transfer equation. This procedure is repeated until a temperature distribution is obtained which satisfies a convergence criterion of Prabhakara and Hogan, specifically, that at any level in the atmosphere the temperature does not change more than 0.1°K in two successive iterations.

The models of Prabhakara and Hogan (1965) predate the results of Mariner IV and the recent Earth-based spectroscopic studies; hence, the models do not contain the most recent initial atmospheric parameters and should be used with caution when they are employed to establish the boundary conditions for upper atmospheric profiles.⁶

The model of Leovy (1966) was developed as a necessary preliminary to a numerical study which attempts to simulate the atmospheric circulation on Mars. Leovy has gone into great detail to produce a model that will represent the diurnal, seasonal, and latitudinal variation of ground and atmospheric temperatures for an atmosphere with a surface pressure of 5 mb and composed entirely of CO_2 .

The convective-radiative model of Leovy is derived for a two-layer atmosphere; that is, the upper layer contains half the mass of the troposphere and the mass of the stratosphere, and the lower layer contains the other half of the mass of the troposphere. The two-layer approximation used by Leovy for the lower atmosphere of Mars is not adequate to describe the vertical variation of the atmospheric parameters. Leovy's profiles for the atmospheric parameters instead show the diurnal, latitudinal, and seasonal variations. From his profiles for the temperature at an altitude of 2.89 km, Fig. 1 was derived by extrapolation to the ground.

The atmospheric temperature near the Martian surface is given by

$$T_0 \equiv T(h=0) = T_3 + Ah_0 = T_3 + 10.1 \quad (16)$$

where T_3 is the temperature at the reference altitude of 2.89 km, A is the temperature lapse rate ($3.5^\circ\text{K km}^{-1}$), and $h_0 = 2.89$ km. To obtain the ground air temperatures for a given time of day, extrapolations of Leovy's results roughly imply

$$T_0(\text{sunrise}) = T_0(\text{noon}) - \Delta T_0 \quad (17)$$

$$T_0(\text{sunset}) = T_0(\text{noon}) - 1/3 \Delta T_0 \quad (18)$$

$$T_0(\text{midnight}) = T_0(\text{sunrise}) + 1/3 \Delta T_0 \quad (19)$$

where ΔT_0 is the diurnal variation of the ground air temperature and the factor $1/3$ is derived from Figures 3 and 6 of Leovy (1966). Use of Eqs. (16) through (19) plus Figures 4 and 5 from Leovy allows calculation of the variation of the ground air temperature with latitude and season as was done in Fig. 1.⁷

Lower Atmosphere Models I, II, and III (Figs. 2 through 10)

These models are based on the general theory given on pages 2 through 5 and, in part, on the types of contemporary models discussed on pages 5 through 7. The models all use interpretations of data from the Mariner IV occultation experiment and the best results of Earth-based observations. The assumptions made in deriving Lower Atmosphere Models I, II, and III are listed below; model parameters all have been adjusted to match the calculated and observational data of Mars given in items 1) through 4).

- 1) Near the base of the thermosphere the kinetic temperature matches the calculated temperature of 155°K derived by Prabhakara and Hogan (1965) based upon radiative equilibrium calculations.
- 2) The temperature profile is assumed linear with temperature gradients which are consistent with the radiative equilibrium calculations of Prabhakara and Hogan (1965) and Anderson (1965).
- 3) The altitude of the Martian tropopause, which is a function of the ground air temperature, is derived from the ingress data of Mariner IV and radiative equilibrium calculations.
- 4) The thermodynamic parameters (specifically pressure and density) for the lower atmosphere of Mars are derived from the equation of hydrostatic equilibrium.
- 5) The lower atmosphere of Mars is assumed to be in a state of hydrostatic equilibrium above the tropopause.
- 6) Gas in the lower atmosphere of Mars is assumed to obey the ideal equation of state.
- 7) Aerosol concentration of the atmosphere is assumed negligible.
- 8) Convective transport is assumed to be the dominant mechanism for energy transport in the troposphere and negligible above; radiative transport is assumed to dominate in the stratosphere.
- 9) The effect of circulation has not been included in the atmospheric models.
- 10) Latitudinal, seasonal, and diurnal variations of the atmospheric parameters are included as significant effects in the description for the lower Martian atmosphere (see Fig. 1).⁷
- 11) Storm activity is assumed negligible.
- 12) Solar activity has not been included in the models.
- 13) Formation of dry ice (condensed CO₂) is assumed negligible.
- 14) The phenomenon of the "blue haze" has been ignored.⁸

CONCLUSIONS

Lower Atmosphere Model I (Figs. 2 through 4), with surface pressure of 10 mb and composition of 80% CO₂, 10% Ar, and 10% N₂, is recommended at this time. Figure 1 gives detailed instructions for use of this model.

Contemporary models of the lower atmosphere of Mars which are presented in Fig. 11 are all post-Mariner IV, the model of Prabhakara and Hogan (1965) thereby being excluded. From Fig. 11 we see that there is general consistency among the various atmospheric parameters assumed for the theories. The atmospheric composition assumed is primarily CO₂ with trace amounts of N₂ and Ar. Ohring et al. (1967) prefer an atmospheric composition for the lower Martian atmosphere of 74% CO₂ and 26% N₂. The surface pressure used in these models was 5 mb except for Ohring et al. (1967), who preferred 7 mb. Values of the mean ground air temperatures are difficult quantities to establish with any reasonable certainty. The values used in these models are believed to represent the most reasonable estimates to date. The altitude of the base of the mesosphere is a highly uncertain quantity; two estimates are given in Fig. 11.

Latitude	To Ground air temperature, °K				To Ground air temperature, °K			
	Noon	Sunset	Midnight	Sunrise	Noon	Sunset	Midnight	Sunrise
	Summer				Winter			
+90	235	235	235	235	143	143	143	143
+70	260	247	235	220	143	143	143	143
+50	265	249	233	217	177	170	162	155
+30	265	248	232	215	225	212	198	185
+10	260	243	227	210	245	230	215	200
-10	245	230	215	200	260	243	227	210
-30	225	212	198	185	265	248	232	215
-50	177	170	162	155	265	249	233	217
-70	143	143	143	143	260	247	235	220
-90	143	143	143	143	235	235	235	235
	Fall				Spring			
+90	143	143	143	143	143	143	143	143
+70	190	181	171	162	208	197	187	176
+50	235	221	206	193	235	220	205	190
+30	250	234	219	203	250	234	217	201
+10	257	241	224	208	260	243	226	209
-10	260	243	226	209	257	241	224	208
-30	250	234	217	201	250	234	219	203
-50	235	220	205	190	235	221	206	193
-70	208	197	187	176	190	181	171	162
-90	143	143	143	143	143	143	143	143
Note: The ground air temperatures are derived neglecting atmospheric circulation and should be used with caution.								

Fig. 1. Table of ground air temperatures for Mars referred to northern seasons. Data are the results of calculations from Leovy (1966) and Neubauer (1966). Leovy presents the calculated thermal data in graphic form, from which the table is derived.

To use Lower Atmosphere Models I, II, and III (Figs. 2 through 10), first refer to Fig. 1 and read the appropriate ground air temperature for the pertinent season, latitude, and time of day. Then select the profile with the most nearly correct value for ground air temperature from among the 10 profiles given for each model.

Data for Models I, II, and III are reproduced essentially in the original computer printout format. The "E" or exponent notation following each number in the figures indicates the power of ten by which the number must be multiplied; e.g., 0.100E 06 = 0.100×10^6 . A positive exponent is denoted by a blank after the E rather than by a plus sign. All exponents are positive with the single exception of those associated with zero altitude. Zero altitude is always followed on the printout by a large negative exponent, a characteristic of the computer.

H Height above mean surface, cm	Atmospheric parameters			Atmospheric parameters		
	T Kinetic temperature, °K	P Total pressure, dyne cm ⁻²	N Total concentration, cm ⁻³	T Kinetic temperature, °K	P Total pressure, dyne cm ⁻²	N Total concentration, cm ⁻³
	Ground air temperature T ₀ : 180°K			Ground air temperature T ₀ : 200°K		
0.000E-38	0.180000E 03	0.100000E 05	0.402442E 18	0.200000E 03	0.100000E 05	0.362198E 18
0.100E 06	0.178511E 03	0.900326E 04	0.365351E 18	0.194887E 03	0.908307E 04	0.337619E 18
0.200E 06	0.178431E 03	0.810835E 04	0.329183E 18	0.192773E 03	0.824143E 04	0.309694E 18
0.300E 06	0.178351E 03	0.730205E 04	0.296582E 18	0.192373E 03	0.747936E 04	0.281642E 18
0.400E 06	0.178271E 03	0.657562E 04	0.267197E 18	0.191973E 03	0.678639E 04	0.256080E 18
0.500E 06	0.178191E 03	0.592118E 04	0.240712E 18	0.191573E 03	0.615637E 04	0.232792E 18
0.600E 06	0.178111E 03	0.533161E 04	0.216842E 18	0.191173E 03	0.558371E 04	0.211579E 18
0.700E 06	0.178031E 03	0.480053E 04	0.195330E 18	0.190773E 03	0.506327E 04	0.192261E 18
0.800E 06	0.177951E 03	0.432214E 04	0.175944E 18	0.190373E 03	0.459041E 04	0.174672E 18
0.900E 06	0.177871E 03	0.389125E 04	0.158474E 18	0.189973E 03	0.416084E 04	0.158660E 18
0.100E 07	0.177791E 03	0.350314E 04	0.142733E 18	0.189573E 03	0.377070E 04	0.144086E 18
0.150E 07	0.177391E 03	0.207011E 04	0.845352E 17	0.187573E 03	0.229753E 04	0.887292E 17
0.200E 07	0.176991E 03	0.122184E 04	0.500079E 17	0.185573E 03	0.139249E 04	0.543569E 17
0.250E 07	0.176591E 03	0.720306E 03	0.295477E 17	0.183573E 03	0.839399E 03	0.331235E 17
0.300E 07	0.176191E 03	0.424129E 03	0.174377E 17	0.181573E 03	0.503195E 03	0.200753E 17
0.350E 07	0.175791E 03	0.249435E 03	0.102787E 17	0.179573E 03	0.299946E 03	0.120998E 17
0.400E 07	0.175391E 03	0.146518E 03	0.605145E 16	0.177573E 03	0.177759E 03	0.725156E 16
0.450E 07	0.174991E 03	0.859603E 02	0.355842E 16	0.175573E 03	0.104724E 03	0.432083E 16
0.500E 07	0.174591E 03	0.503704E 02	0.208991E 16	0.173573E 03	0.613241E 02	0.255933E 16
0.550E 07	0.171000E 03	0.296967E 02	0.125802E 16	0.171000E 03	0.361547E 02	0.153160E 16
0.600E 07	0.167000E 03	0.172906E 02	0.750015E 15	0.167000E 03	0.210507E 02	0.913117E 15
0.650E 07	0.163000E 03	0.993613E 01	0.441576E 15	0.163000E 03	0.120969E 02	0.537604E 15
0.700E 07	0.159000E 03	0.563178E 01	0.256581E 15	0.159000E 03	0.685650E 01	0.312379E 15
0.750E 07	0.155000E 03	0.314624E 01	0.147040E 15	0.155000E 03	0.383044E 01	0.179016E 15
0.800E 07	0.155000E 03	0.175598E 01	0.820661E 14	0.155000E 03	0.213784E 01	0.999125E 14
0.850E 07	0.155000E 03	0.980045E 00	0.458027E 14	0.155000E 03	0.119317E 01	0.557631E 14
0.900E 07	0.155000E 03	0.546982E 00	0.255634E 14	0.155000E 03	0.665932E 00	0.311225E 14
	Ground air temperature T ₀ : 190°K			Ground air temperature T ₀ : 210°K		
0.000E-38	0.190000E 03	0.100000E 05	0.381261E 18	0.210000E 03	0.100000E 05	0.344951E 18
0.100E 06	0.185720E 03	0.903950E 04	0.352584E 18	0.204950E 03	0.912541E 04	0.322538E 18
0.200E 06	0.185480E 03	0.817378E 04	0.319230E 18	0.200309E 03	0.830953E 04	0.300506E 18
0.300E 06	0.185240E 03	0.739002E 04	0.288993E 18	0.199749E 03	0.756849E 04	0.274474E 18
0.400E 06	0.185000E 03	0.668053E 04	0.261587E 18	0.199189E 03	0.689172E 04	0.250634E 18
0.500E 06	0.184760E 03	0.603837E 04	0.236749E 18	0.198629E 03	0.627382E 04	0.228806E 18
0.600E 06	0.184520E 03	0.545721E 04	0.214242E 18	0.198069E 03	0.570980E 04	0.208825E 18
0.700E 06	0.184280E 03	0.493134E 04	0.193849E 18	0.197509E 03	0.519510E 04	0.190539E 18
0.800E 06	0.184040E 03	0.445556E 04	0.175375E 18	0.196949E 03	0.472553E 04	0.173810E 18
0.900E 06	0.183800E 03	0.402515E 04	0.158640E 18	0.196389E 03	0.429725E 04	0.158508E 18
0.100E 07	0.183560E 03	0.363583E 04	0.143484E 18	0.195829E 03	0.390672E 04	0.144515E 18
0.150E 07	0.182360E 03	0.218194E 04	0.866742E 17	0.193029E 03	0.241618E 04	0.906742E 17
0.200E 07	0.181160E 03	0.130502E 04	0.521833E 17	0.190229E 03	0.148387E 04	0.565064E 17
0.250E 07	0.179960E 03	0.777872E 03	0.313119E 17	0.187429E 03	0.904743E 03	0.349676E 17
0.300E 07	0.178760E 03	0.462057E 03	0.187242E 17	0.184629E 03	0.547544E 03	0.214831E 17
0.350E 07	0.177560E 03	0.273502E 03	0.111581E 17	0.181829E 03	0.328836E 03	0.131007E 17
0.400E 07	0.176360E 03	0.161317E 03	0.662608E 16	0.179029E 03	0.195931E 03	0.792790E 16
0.450E 07	0.175160E 03	0.948056E 02	0.392081E 16	0.176229E 03	0.115793E 03	0.475974E 16
0.500E 07	0.173960E 03	0.555138E 02	0.231169E 16	0.173429E 03	0.678585E 02	0.283439E 16
0.550E 07	0.171000E 03	0.327292E 02	0.138648E 16	0.171000E 03	0.400072E 02	0.169480E 16
0.600E 07	0.167000E 03	0.190562E 02	0.826602E 15	0.167000E 03	0.232938E 02	0.101041E 16
0.650E 07	0.163000E 03	0.109507E 02	0.486667E 15	0.163000E 03	0.133859E 02	0.594888E 15
0.700E 07	0.159000E 03	0.620686E 01	0.282782E 15	0.159000E 03	0.758709E 01	0.345664E 15
0.750E 07	0.155000E 03	0.346751E 01	0.162055E 15	0.155000E 03	0.423859E 01	0.198091E 15
0.800E 07	0.155000E 03	0.193529E 01	0.904461E 14	0.155000E 03	0.236564E 01	0.110559E 15
0.850E 07	0.155000E 03	0.108012E 01	0.504797E 14	0.155000E 03	0.132031E 01	0.617049E 14
0.900E 07	0.155000E 03	0.602837E 00	0.281737E 14	0.155000E 03	0.736890E 00	0.344387E 14

Fig. 2. Lower Atmosphere Model I for ground air temperatures 180, 190, 200, and 210°K. Surface pressure 10 mb (0.10×10^5 dyne cm⁻²); atmospheric abundance 80% CO₂, 10% Ar, 10% N₂ by volume; mean molecular mass of atmospheric constituents 0.697119×10^{-22} gm.

H Height above mean surface, cm	Atmospheric parameters			Atmospheric parameters		
	T Kinetic temperature, °K	P Total pressure, dyne cm ⁻²	N Total concentration, cm ⁻³	T Kinetic temperature, °K	P Total pressure, dyne cm ⁻²	N Total concentration, cm ⁻³
	Ground air temperature T ₀ : 220°K			Ground air temperature T ₀ : 240°K		
0.000E-38	0.220000E 03	0.100000E 05	0.329271E 18	0.240000E 03	0.100000E 05	0.301832E 18
0.100E 06	0.215012E 03	0.916401E 04	0.308744E 18	0.235131E 03	0.923182E 04	0.284415E 18
0.200E 06	0.210024E 03	0.838072E 04	0.289060E 18	0.230263E 03	0.850841E 04	0.267671E 18
0.300E 06	0.207364E 03	0.765619E 04	0.267458E 18	0.225394E 03	0.782803E 04	0.251586E 18
0.400E 06	0.206644E 03	0.699540E 04	0.245225E 18	0.222266E 03	0.719450E 04	0.234479E 18
0.500E 06	0.205924E 03	0.638962E 04	0.224773E 18	0.221226E 03	0.661312E 04	0.216544E 18
0.600E 06	0.205204E 03	0.583445E 04	0.205963E 18	0.220186E 03	0.607630E 04	0.199906E 18
0.700E 06	0.204484E 03	0.532582E 04	0.188670E 18	0.219146E 03	0.558082E 04	0.184477E 18
0.800E 06	0.203764E 03	0.485996E 04	0.172775E 18	0.218106E 03	0.512368E 04	0.170173E 18
0.900E 06	0.203044E 03	0.443342E 04	0.158170E 18	0.217066E 03	0.470205E 04	0.156918E 18
0.100E 07	0.202324E 03	0.404299E 04	0.144754E 18	0.216026E 03	0.431335E 04	0.144639E 18
0.150E 07	0.198724E 03	0.253724E 04	0.924884E 17	0.210826E 03	0.278420E 04	0.956650E 17
0.200E 07	0.195124E 03	0.157878E 04	0.586120E 17	0.205626E 03	0.177762E 04	0.626235E 17
0.250E 07	0.191524E 03	0.973742E 03	0.368296E 17	0.200426E 03	0.112198E 04	0.405516E 17
0.300E 07	0.187924E 03	0.595092E 03	0.229392E 17	0.195226E 03	0.699644E 03	0.259607E 17
0.350E 07	0.184324E 03	0.360236E 03	0.141573E 17	0.190026E 03	0.430757E 03	0.164209E 17
0.400E 07	0.180724E 03	0.215919E 03	0.865467E 16	0.184826E 03	0.261663E 03	0.102555E 17
0.450E 07	0.177124E 03	0.128092E 03	0.523865E 16	0.179626E 03	0.156702E 03	0.631948E 16
0.500E 07	0.173524E 03	0.751786E 02	0.313842E 16	0.174426E 03	0.924407E 02	0.383910E 16
0.550E 07	0.171000E 03	0.443229E 02	0.187762E 16	0.171000E 03	0.545001E 02	0.230875E 16
0.600E 07	0.167000E 03	0.258065E 02	0.111941E 16	0.167000E 03	0.317321E 02	0.137644E 16
0.650E 07	0.163000E 03	0.148298E 02	0.659060E 15	0.163000E 03	0.182350E 02	0.810390E 15
0.700E 07	0.159000E 03	0.840554E 01	0.382952E 15	0.159000E 03	0.103356E 02	0.470883E 15
0.750E 07	0.155000E 03	0.469582E 01	0.219460E 15	0.155000E 03	0.577405E 01	0.269851E 15
0.800E 07	0.155000E 03	0.262083E 01	0.122485E 15	0.155000E 03	0.322261E 01	0.150609E 15
0.850E 07	0.155000E 03	0.146273E 01	0.683613E 14	0.155000E 03	0.179860E 01	0.840580E 14
0.900E 07	0.155000E 03	0.816381E 00	0.381537E 14	0.155000E 03	0.100383E 01	0.469144E 14
	Ground air temperature T ₀ : 230°K			Ground air temperature T ₀ : 250°K		
0.000E-38	0.230000E 03	0.100000E 05	0.314955E 18	0.250000E 03	0.100000E 05	0.289758E 18
0.100E 06	0.225072E 03	0.919935E 04	0.296081E 18	0.245189E 03	0.926176E 04	0.273633E 18
0.200E 06	0.220145E 03	0.844719E 04	0.277958E 18	0.240378E 03	0.856499E 04	0.258112E 18
0.300E 06	0.215217E 03	0.774156E 04	0.260572E 18	0.235567E 03	0.790813E 04	0.243185E 18
0.400E 06	0.214337E 03	0.709654E 04	0.239842E 18	0.230756E 03	0.728963E 04	0.228839E 18
0.500E 06	0.213457E 03	0.650294E 04	0.220686E 18	0.229227E 03	0.671967E 04	0.212353E 18
0.600E 06	0.212577E 03	0.595683E 04	0.202990E 18	0.228027E 03	0.619235E 04	0.196718E 18
0.700E 06	0.211697E 03	0.545461E 04	0.186649E 18	0.226827E 03	0.570394E 04	0.182161E 18
0.800E 06	0.210817E 03	0.499289E 04	0.171563E 18	0.225627E 03	0.525177E 04	0.168613E 18
0.900E 06	0.209937E 03	0.456857E 04	0.157640E 18	0.224427E 03	0.483331E 04	0.156007E 18
0.100E 07	0.209057E 03	0.417875E 04	0.144796E 18	0.223227E 03	0.444622E 04	0.144284E 18
0.150E 07	0.204657E 03	0.266010E 04	0.941558E 17	0.217227E 03	0.290901E 04	0.970081E 17
0.200E 07	0.200257E 03	0.167682E 04	0.606561E 17	0.211227E 03	0.188079E 04	0.645010E 17
0.250E 07	0.195857E 03	0.104622E 04	0.386954E 17	0.205227E 03	0.120082E 04	0.423855E 17
0.300E 07	0.191457E 03	0.645808E 03	0.244347E 17	0.199227E 03	0.756537E 03	0.275079E 17
0.350E 07	0.187057E 03	0.394196E 03	0.152656E 17	0.193227E 03	0.469945E 03	0.176179E 17
0.400E 07	0.182657E 03	0.237803E 03	0.943099E 16	0.187227E 03	0.287569E 03	0.111263E 17
0.450E 07	0.178257E 03	0.141701E 03	0.575838E 16	0.181227E 03	0.173176E 03	0.692214E 16
0.500E 07	0.173857E 03	0.833499E 02	0.347287E 16	0.175227E 03	0.102522E 03	0.423831E 16
0.550E 07	0.171000E 03	0.491404E 02	0.208170E 16	0.171000E 03	0.604437E 02	0.256054E 16
0.600E 07	0.167000E 03	0.286115E 02	0.124108E 16	0.167000E 03	0.351927E 02	0.152656E 16
0.650E 07	0.163000E 03	0.164417E 02	0.730694E 15	0.163000E 03	0.202237E 02	0.898770E 15
0.700E 07	0.159000E 03	0.931914E 01	0.424575E 15	0.159000E 03	0.114627E 02	0.522237E 15
0.750E 07	0.155000E 03	0.520621E 01	0.243314E 15	0.155000E 03	0.640376E 01	0.299281E 15
0.800E 07	0.155000E 03	0.290569E 01	0.135798E 15	0.155000E 03	0.357406E 01	0.167035E 15
0.850E 07	0.155000E 03	0.162172E 01	0.757915E 14	0.155000E 03	0.199475E 01	0.932252E 14
0.900E 07	0.155000E 03	0.905114E 00	0.423007E 14	0.155000E 03	0.111331E 01	0.520308E 14

Fig. 3. Lower Atmosphere Model I for ground air temperatures 220, 230, 240, and 250°K. Surface pressure 10 mb (0.10×10^5 dyne cm⁻²); atmospheric abundance 80% CO₂, 10% Ar, 10% N₂ by volume; mean molecular mass of atmospheric constituents 0.697119×10^{-22} gm.

H Height above mean surface, cm	Atmospheric parameters			Atmospheric parameters		
	T Kinetic temperature, °K	P Total pressure, dyne cm ⁻²	N Total concentration, cm ⁻³	T Kinetic temperature, °K	P Total pressure, dyne cm ⁻²	N Total concentration, cm ⁻³
	Ground air temperature T ₀ : 270°K			Ground air temperature T ₀ : 290°K		
0.000E-38	0.270000E 03	0.100000E 05	0.268295E 18	0.290000E 03	0.100000E 05	0.249792E 18
0.100E 06	0.265300E 03	0.931514E 04	0.254348E 18	0.285406E 03	0.936132E 04	0.237602E 18
0.200E 06	0.260600E 03	0.866619E 04	0.240896E 18	0.280812E 03	0.875405E 04	0.225824E 18
0.300E 06	0.255900E 03	0.805186E 04	0.227930E 18	0.276218E 03	0.817712E 04	0.214449E 18
0.400E 06	0.251200E 03	0.747089E 04	0.215441E 18	0.271624E 03	0.762949E 04	0.203471E 18
0.500E 06	0.246500E 03	0.692203E 04	0.203420E 18	0.267030E 03	0.711012E 04	0.192882E 18
0.600E 06	0.244402E 03	0.641275E 04	0.190071E 18	0.262436E 03	0.661800E 04	0.182675E 18
0.700E 06	0.242882E 03	0.593934E 04	0.177141E 18	0.259845E 03	0.615862E 04	0.171690E 18
0.800E 06	0.241362E 03	0.549824E 04	0.165018E 18	0.258005E 03	0.572985E 04	0.160876E 18
0.900E 06	0.239842E 03	0.508741E 04	0.153656E 18	0.256165E 03	0.532818E 04	0.150673E 18
0.100E 07	0.238322E 03	0.470496E 04	0.143011E 18	0.254325E 03	0.495208E 04	0.141050E 18
0.150E 07	0.230722E 03	0.315891E 04	0.991802E 17	0.245125E 03	0.340642E 04	0.100667E 18
0.200E 07	0.223122E 03	0.209277E 04	0.679448E 17	0.235925E 03	0.230989E 04	0.709240E 17
0.250E 07	0.215522E 03	0.136681E 04	0.459404E 17	0.226725E 03	0.154232E 04	0.492777E 17
0.300E 07	0.207922E 03	0.879132E 03	0.306289E 17	0.217525E 03	0.101272E 04	0.337252E 17
0.350E 07	0.200322E 03	0.556239E 03	0.201145E 17	0.208325E 03	0.652991E 03	0.227061E 17
0.400E 07	0.192722E 03	0.345764E 03	0.129965E 17	0.199125E 03	0.412778E 03	0.150164E 17
0.450E 07	0.185122E 03	0.210857E 03	0.825101E 16	0.189925E 03	0.255330E 03	0.973859E 16
0.500E 07	0.177522E 03	0.125948E 03	0.513945E 16	0.180725E 03	0.154215E 03	0.618137E 16
0.550E 07	0.171000E 03	0.742549E 02	0.314561E 16	0.171000E 03	0.909203E 02	0.385160E 16
0.600E 07	0.167000E 03	0.432342E 02	0.187537E 16	0.167000E 03	0.529374E 02	0.229627E 16
0.650E 07	0.163000E 03	0.248447E 02	0.110414E 16	0.163000E 03	0.304207E 02	0.135194E 16
0.700E 07	0.159000E 03	0.140819E 02	0.641567E 15	0.159000E 03	0.172424E 02	0.785556E 15
0.750E 07	0.155000E 03	0.786699E 01	0.367666E 15	0.155000E 03	0.963262E 01	0.450183E 15
0.800E 07	0.155000E 03	0.439072E 01	0.205201E 15	0.155000E 03	0.537615E 01	0.251256E 15
0.850E 07	0.155000E 03	0.245055E 01	0.114527E 15	0.155000E 03	0.300053E 01	0.140231E 15
0.900E 07	0.155000E 03	0.136770E 01	0.639197E 14	0.155000E 03	0.167466E 01	0.782654E 14

Fig. 4. Lower Atmosphere Model I for ground air temperatures 270 and 290°K. Surface pressure 10 mb (0.10×10^5 dyne cm⁻²); atmospheric abundance 80% CO₂, 10% Ar, 10% N₂ by volume; mean molecular mass of atmospheric constituents 0.697119×10^{-22} gm.

H Height above mean surface, cm	Atmospheric parameters			Atmospheric parameters		
	T Kinetic temperature, °K	P Total pressure, dyne cm ⁻²	N Total concentration, cm ⁻³	T Kinetic temperature, °K	P Total pressure, dyne cm ⁻²	N Total concentration, cm ⁻³
	Ground air temperature T ₀ : 180°K			Ground air temperature T ₀ : 200°K		
0.000E-38	0.180000E 03	0.100000E 05	0.402442E 18	0.200000E 03	0.100000E 05	0.362198E 18
0.100E 06	0.178519E 03	0.904843E 04	0.367169E 18	0.194885E 03	0.912476E 04	0.339171E 18
0.200E 06	0.178439E 03	0.818978E 04	0.332475E 18	0.192771E 03	0.831767E 04	0.312563E 18
0.300E 06	0.178359E 03	0.741230E 04	0.301048E 18	0.192371E 03	0.758351E 04	0.285567E 18
0.400E 06	0.178279E 03	0.670832E 04	0.272578E 18	0.191971E 03	0.691281E 04	0.260853E 18
0.500E 06	0.178199E 03	0.607092E 04	0.246789E 18	0.191571E 03	0.630022E 04	0.238234E 18
0.600E 06	0.178119E 03	0.549385E 04	0.223431E 18	0.191171E 03	0.574080E 04	0.217534E 18
0.700E 06	0.178039E 03	0.497140E 04	0.202274E 18	0.190771E 03	0.523003E 04	0.198595E 18
0.800E 06	0.177959E 03	0.449844E 04	0.183113E 18	0.190371E 03	0.476377E 04	0.181271E 18
0.900E 06	0.177879E 03	0.407029E 04	0.165759E 18	0.189971E 03	0.433823E 04	0.165426E 18
0.100E 07	0.177799E 03	0.368272E 04	0.150043E 18	0.189571E 03	0.394992E 04	0.150936E 18
0.150E 07	0.177399E 03	0.223149E 04	0.911213E 17	0.187571E 03	0.246417E 04	0.951662E 17
0.200E 07	0.176999E 03	0.135060E 04	0.552757E 17	0.185571E 03	0.152953E 04	0.597069E 17
0.250E 07	0.176599E 03	0.816524E 03	0.334933E 17	0.183571E 03	0.944494E 03	0.372711E 17
0.300E 07	0.176199E 03	0.493074E 03	0.202715E 17	0.181571E 03	0.580159E 03	0.231461E 17
0.350E 07	0.175799E 03	0.297413E 03	0.122552E 17	0.179571E 03	0.354447E 03	0.142986E 17
0.400E 07	0.175399E 03	0.179187E 03	0.740043E 16	0.177571E 03	0.215357E 03	0.878543E 16
0.450E 07	0.174999E 03	0.107833E 03	0.446368E 16	0.175571E 03	0.130111E 03	0.536832E 16
0.500E 07	0.174599E 03	0.648174E 02	0.268922E 16	0.173571E 03	0.781560E 02	0.326184E 16
0.550E 07	0.171000E 03	0.391880E 02	0.166009E 16	0.171000E 03	0.472524E 02	0.200172E 16
0.600E 07	0.167000E 03	0.234121E 02	0.101555E 16	0.167000E 03	0.282301E 02	0.122454E 16
0.650E 07	0.163000E 03	0.138135E 02	0.613894E 15	0.163000E 03	0.166562E 02	0.740226E 15
0.700E 07	0.159000E 03	0.804407E 01	0.366484E 15	0.159000E 03	0.969944E 01	0.441902E 15
0.750E 07	0.155000E 03	0.462023E 01	0.215927E 15	0.155000E 03	0.557101E 01	0.260363E 15
0.800E 07	0.155000E 03	0.265126E 01	0.123907E 15	0.155000E 03	0.319685E 01	0.149406E 15
0.850E 07	0.155000E 03	0.152139E 01	0.711024E 14	0.155000E 03	0.183447E 01	0.857345E 14
0.900E 07	0.155000E 03	0.873028E 00	0.408012E 14	0.155000E 03	0.105269E 01	0.491976E 14
	Ground air temperature T ₀ : 190°K			Ground air temperature T ₀ : 210°K		
0.000E-38	0.190000E 03	0.100000E 05	0.381261E 18	0.210000E 03	0.100000E 05	0.344951E 18
0.100E 06	0.185730E 03	0.908310E 04	0.354266E 18	0.204935E 03	0.916524E 04	0.323969E 18
0.200E 06	0.185490E 03	0.825272E 04	0.322295E 18	0.200280E 03	0.838302E 04	0.303207E 18
0.300E 06	0.185250E 03	0.749733E 04	0.293174E 18	0.199720E 03	0.766937E 04	0.278173E 18
0.400E 06	0.185010E 03	0.681023E 04	0.266651E 18	0.199160E 03	0.701472E 04	0.255143E 18
0.500E 06	0.184770E 03	0.618533E 04	0.242498E 18	0.198600E 03	0.641433E 04	0.233964E 18
0.600E 06	0.184530E 03	0.561707E 04	0.220506E 18	0.198040E 03	0.586385E 04	0.214490E 18
0.700E 06	0.184290E 03	0.510037E 04	0.200483E 18	0.197480E 03	0.535925E 04	0.196588E 18
0.800E 06	0.184050E 03	0.463062E 04	0.182255E 18	0.196920E 03	0.489683E 04	0.180136E 18
0.900E 06	0.183810E 03	0.420361E 04	0.165665E 18	0.196360E 03	0.447315E 04	0.165020E 18
0.100E 07	0.183570E 03	0.381548E 04	0.150565E 18	0.195800E 03	0.408507E 04	0.151134E 18
0.150E 07	0.182370E 03	0.234618E 04	0.931933E 17	0.193000E 03	0.258479E 04	0.970163E 17
0.200E 07	0.181170E 03	0.143806E 04	0.575001E 17	0.190200E 03	0.162460E 04	0.618746E 17
0.250E 07	0.179970E 03	0.878581E 03	0.353638E 17	0.187400E 03	0.101409E 04	0.391997E 17
0.300E 07	0.178770E 03	0.535001E 03	0.216789E 17	0.184600E 03	0.628528E 03	0.246643E 17
0.350E 07	0.177570E 03	0.324695E 03	0.132460E 17	0.181800E 03	0.386721E 03	0.154092E 17
0.400E 07	0.176370E 03	0.196393E 03	0.806639E 16	0.179000E 03	0.236155E 03	0.955698E 16
0.450E 07	0.175170E 03	0.118382E 03	0.489558E 16	0.176200E 03	0.143093E 03	0.588288E 16
0.500E 07	0.173970E 03	0.711108E 02	0.296100E 16	0.173400E 03	0.860115E 02	0.359322E 16
0.550E 07	0.171000E 03	0.429929E 02	0.182128E 16	0.171000E 03	0.520017E 02	0.220291E 16
0.600E 07	0.167000E 03	0.256853E 02	0.111415E 16	0.167000E 03	0.310674E 02	0.134761E 16
0.650E 07	0.163000E 03	0.151548E 02	0.673500E 15	0.163000E 03	0.183303E 02	0.814626E 15
0.700E 07	0.159000E 03	0.882511E 01	0.402068E 15	0.159000E 03	0.106743E 02	0.486317E 15
0.750E 07	0.155000E 03	0.506883E 01	0.236893E 15	0.155000E 03	0.613095E 01	0.286532E 15
0.800E 07	0.155000E 03	0.290868E 01	0.135938E 15	0.155000E 03	0.351817E 01	0.164422E 15
0.850E 07	0.155000E 03	0.166911E 01	0.780062E 14	0.155000E 03	0.201885E 01	0.943516E 14
0.900E 07	0.155000E 03	0.957795E 00	0.447628E 14	0.155000E 03	0.115849E 01	0.541424E 14

Fig. 5. Lower Atmosphere Model II for ground air temperatures 180, 190, 200, and 210°K. Surface pressure 10 mb (0.10×10^5 dyne cm⁻²); atmospheric abundance 60% CO₂, 20% Ar, 20% N₂ by volume; mean molecular mass of atmospheric constituents 0.663921×10^{-22} gm.

H Height above mean surface, cm	Atmospheric parameters			Atmospheric parameters		
	T Kinetic temperature, °K	P Total pressure, dyne cm ⁻²	N Total concentration, cm ⁻³	T Kinetic temperature, °K	P Total pressure, dyne cm ⁻²	N Total concentration, cm ⁻³
	Ground air temperature T ₀ : 220°K			Ground air temperature T ₀ : 240°K		
0.000E-38	0.220000E 03	0.100000E 05	0.329271E 18	0.240000E 03	0.100000E 05	0.301832E 18
0.100E 06	0.214984E 03	0.920214E 04	0.310069E 18	0.235080E 03	0.926695E 04	0.285560E 18
0.200E 06	0.209969E 03	0.845134E 04	0.291573E 18	0.230160E 03	0.857382E 04	0.269849E 18
0.300E 06	0.207296E 03	0.775381E 04	0.270957E 18	0.225240E 03	0.791922E 04	0.254691E 18
0.400E 06	0.206576E 03	0.711490E 04	0.249497E 18	0.222083E 03	0.730716E 04	0.238347E 18
0.500E 06	0.205856E 03	0.652669E 04	0.229670E 18	0.221043E 03	0.674323E 04	0.220987E 18
0.600E 06	0.205136E 03	0.598529E 04	0.211358E 18	0.220003E 03	0.622047E 04	0.204819E 18
0.700E 06	0.204416E 03	0.548713E 04	0.194449E 18	0.218963E 03	0.573604E 04	0.189766E 18
0.800E 06	0.203696E 03	0.502889E 04	0.178840E 18	0.217923E 03	0.528730E 04	0.175755E 18
0.900E 06	0.202976E 03	0.460750E 04	0.164436E 18	0.216883E 03	0.487176E 04	0.162718E 18
0.100E 07	0.202256E 03	0.422010E 04	0.151146E 18	0.215843E 03	0.448711E 04	0.150593E 18
0.150E 07	0.198656E 03	0.270740E 04	0.987249E 17	0.210643E 03	0.295632E 04	0.101667E 18
0.200E 07	0.195056E 03	0.172289E 04	0.639842E 17	0.205443E 03	0.192755E 04	0.679659E 17
0.250E 07	0.191456E 03	0.108719E 04	0.411349E 17	0.200243E 03	0.124308E 04	0.449694E 17
0.300E 07	0.187856E 03	0.680072E 03	0.262244E 17	0.195043E 03	0.792462E 03	0.294323E 17
0.350E 07	0.184256E 03	0.421564E 03	0.165736E 17	0.189843E 03	0.499085E 03	0.190439E 17
0.400E 07	0.180656E 03	0.258866E 03	0.103800E 17	0.184643E 03	0.310308E 03	0.121741E 17
0.450E 07	0.177056E 03	0.157406E 03	0.644002E 16	0.179443E 03	0.190333E 03	0.768360E 16
0.500E 07	0.173456E 03	0.947395E 02	0.395656E 16	0.174243E 03	0.115079E 03	0.478427E 16
0.550E 07	0.171000E 03	0.572786E 02	0.242645E 16	0.171000E 03	0.695754E 02	0.294738E 16
0.600E 07	0.167000E 03	0.342200E 02	0.148436E 16	0.167000E 03	0.415666E 02	0.180303E 16
0.650E 07	0.163000E 03	0.201904E 02	0.897291E 15	0.163000E 03	0.245250E 02	0.108993E 16
0.700E 07	0.159000E 03	0.117575E 02	0.535666E 15	0.159000E 03	0.142817E 02	0.650666E 15
0.750E 07	0.155000E 03	0.675309E 01	0.315607E 15	0.155000E 03	0.820289E 01	0.383364E 15
0.800E 07	0.155000E 03	0.387517E 01	0.181107E 15	0.155000E 03	0.470712E 01	0.219988E 15
0.850E 07	0.155000E 03	0.222372E 01	0.103926E 15	0.155000E 03	0.270112E 01	0.126237E 15
0.900E 07	0.155000E 03	0.127605E 01	0.596365E 14	0.155000E 03	0.155000E 01	0.724396E 14
	Ground air temperature T ₀ : 230°K			Ground air temperature T ₀ : 250°K		
0.000E-38	0.230000E 03	0.100000E 05	0.314955E 18	0.250000E 03	0.100000E 05	0.289758E 18
0.100E 06	0.225033E 03	0.923592E 04	0.297311E 18	0.245126E 03	0.929556E 04	0.274702E 18
0.200E 06	0.220065E 03	0.851510E 04	0.280294E 18	0.240252E 03	0.862808E 04	0.260149E 18
0.300E 06	0.215098E 03	0.783598E 04	0.263897E 18	0.235379E 03	0.799631E 04	0.246093E 18
0.400E 06	0.214218E 03	0.721258E 04	0.243900E 18	0.230505E 03	0.739901E 04	0.232525E 18
0.500E 06	0.213338E 03	0.663652E 04	0.225345E 18	0.228971E 03	0.684640E 04	0.216600E 18
0.600E 06	0.212458E 03	0.610436E 04	0.208134E 18	0.227771E 03	0.633318E 04	0.201419E 18
0.700E 06	0.211578E 03	0.561292E 04	0.192174E 18	0.226571E 03	0.585602E 04	0.187230E 18
0.800E 06	0.210698E 03	0.515925E 04	0.177379E 18	0.225371E 03	0.541256E 04	0.173973E 18
0.900E 06	0.209818E 03	0.474057E 04	0.163668E 18	0.224171E 03	0.500057E 04	0.161591E 18
0.100E 07	0.208938E 03	0.435432E 04	0.150966E 18	0.222971E 03	0.461799E 04	0.150031E 18
0.150E 07	0.204538E 03	0.283142E 04	0.100278E 18	0.216971E 03	0.308161E 04	0.102885E 18
0.200E 07	0.200138E 03	0.182400E 04	0.660194E 17	0.210971E 03	0.203318E 04	0.698118E 17
0.250E 07	0.195738E 03	0.116358E 04	0.430625E 17	0.204971E 03	0.132545E 04	0.468432E 17
0.300E 07	0.191338E 03	0.734739E 03	0.278169E 17	0.198971E 03	0.853157E 03	0.310610E 17
0.350E 07	0.186938E 03	0.459011E 03	0.177870E 17	0.192971E 03	0.541796E 03	0.203386E 17
0.400E 07	0.182538E 03	0.283561E 03	0.112530E 17	0.186971E 03	0.339168E 03	0.131406E 17
0.450E 07	0.178138E 03	0.173127E 03	0.704020E 16	0.180971E 03	0.209101E 03	0.836998E 16
0.500E 07	0.173738E 03	0.104406E 03	0.435318E 16	0.174971E 03	0.126828E 03	0.525082E 16
0.550E 07	0.171000E 03	0.631227E 02	0.267403E 16	0.171000E 03	0.766792E 02	0.324831E 16
0.600E 07	0.167000E 03	0.377115E 02	0.163581E 16	0.167000E 03	0.458106E 02	0.198713E 16
0.650E 07	0.163000E 03	0.222504E 02	0.988841E 15	0.163000E 03	0.270290E 02	0.120121E 16
0.700E 07	0.159000E 03	0.129571E 02	0.590321E 15	0.159000E 03	0.157399E 02	0.717101E 15
0.750E 07	0.155000E 03	0.744211E 01	0.347809E 15	0.155000E 03	0.904042E 01	0.422506E 15
0.800E 07	0.155000E 03	0.427056E 01	0.199586E 15	0.155000E 03	0.518772E 01	0.242450E 15
0.850E 07	0.155000E 03	0.245060E 01	0.114530E 15	0.155000E 03	0.297691E 01	0.139126E 15
0.900E 07	0.155000E 03	0.140625E 01	0.657213E 14	0.155000E 03	0.170826E 01	0.798359E 14

Fig. 6. Lower Atmosphere Model II for ground air temperatures 220, 230, 240, and 250°K. Surface pressure 10 mb (0.10×10^5 dyne cm⁻²); atmospheric abundance 60% CO₂, 20% Ar, 20% N₂ by volume; mean molecular mass of atmospheric constituents 0.663921×10^{-22} gm.

H Height above mean surface, cm	Atmospheric parameters			Atmospheric parameters		
	T Kinetic temperature, °K	P Total pressure, dyne cm ⁻²	N Total concentration, cm ⁻³	T Kinetic temperature, °K	P Total pressure, dyne cm ⁻²	N Total concentration, cm ⁻³
	Ground air temperature T ₀ : 270°K			Ground air temperature T ₀ : 290°K		
0.000E-38	0.270000E 03	0.100000E 05	0.268295E 18	0.290000E 03	0.100000E 05	0.249792E 18
0.100E 06	0.265216E 03	0.934657E 04	0.255286E 18	0.285303E 03	0.939068E 04	0.238433E 18
0.200E 06	0.260433E 03	0.872509E 04	0.242689E 18	0.280607E 03	0.880929E 04	0.227415E 18
0.300E 06	0.255649E 03	0.813456E 04	0.230497E 18	0.275910E 03	0.825499E 04	0.216733E 18
0.400E 06	0.250866E 03	0.757396E 04	0.218705E 18	0.271213E 03	0.772694E 04	0.206382E 18
0.500E 06	0.246082E 03	0.704231E 04	0.207306E 18	0.266517E 03	0.722432E 04	0.196358E 18
0.600E 06	0.243969E 03	0.654712E 04	0.194398E 18	0.261820E 03	0.674632E 04	0.186655E 18
0.700E 06	0.242449E 03	0.608519E 04	0.181815E 18	0.250201E 03	0.629851E 04	0.176026E 18
0.800E 06	0.240929E 03	0.565325E 04	0.169975E 18	0.257361E 03	0.587917E 04	0.165481E 18
0.900E 06	0.239409E 03	0.524953E 04	0.158839E 18	0.255521E 03	0.548504E 04	0.155499E 18
0.100E 07	0.237889E 03	0.487233E 04	0.148368E 18	0.253681E 03	0.511476E 04	0.146054E 18
0.150E 07	0.230289E 03	0.333160E 04	0.104799E 18	0.244481E 03	0.357827E 04	0.106024E 18
0.200E 07	0.222689E 03	0.224920E 04	0.731653E 17	0.235281E 03	0.246927E 04	0.760254E 17
0.250E 07	0.215089E 03	0.149788E 04	0.504470E 17	0.226081E 03	0.167895E 04	0.537961E 17
0.300E 07	0.207489E 03	0.983048E 03	0.343207E 17	0.216881E 03	0.112343E 04	0.375234E 17
0.350E 07	0.199889E 03	0.635106E 03	0.230162E 17	0.207681E 03	0.738739E 03	0.257674E 17
0.400E 07	0.192289E 03	0.403425E 03	0.151980E 17	0.198481E 03	0.476634E 03	0.173957E 17
0.450E 07	0.184689E 03	0.251612E 03	0.986885E 16	0.189281E 03	0.301193E 03	0.115269E 17
0.500E 07	0.177089E 03	0.153845E 03	0.629313E 16	0.180081E 03	0.186025E 03	0.748305E 16
0.550E 07	0.171000E 03	0.930129E 02	0.394024E 16	0.171000E 03	0.112469E 03	0.476444E 16
0.600E 07	0.167000E 03	0.555688E 02	0.241041E 16	0.167000E 03	0.671923E 02	0.291460E 16
0.650E 07	0.163000E 03	0.327865E 02	0.145708E 16	0.163000E 03	0.396446E 02	0.176186E 16
0.700E 07	0.159000E 03	0.190927E 02	0.869852E 15	0.159000E 03	0.230863E 02	0.105180E 16
0.750E 07	0.155000E 03	0.109661E 02	0.512505E 15	0.155000E 03	0.132600E 02	0.619707E 15
0.800E 07	0.155000E 03	0.629277E 01	0.294094E 15	0.155000E 03	0.760905E 01	0.355611E 15
0.850E 07	0.155000E 03	0.361103E 01	0.168762E 15	0.155000E 03	0.436635E 01	0.204063E 15
0.900E 07	0.155000E 03	0.207214E 01	0.968419E 14	0.155000E 03	0.250557E 01	0.117099E 15

Fig. 7. Lower Atmosphere Model II for ground air temperatures 270 and 290°K. Surface pressure 10 mb (0.10×10^5 dyne cm⁻²); atmospheric abundance 60% CO₂, 20% Ar, 20% N₂ by volume; mean molecular mass of atmospheric constituents 0.663921×10^{-22} gm.

H Height above mean surface, cm	Atmospheric parameters			Atmospheric parameters		
	T Kinetic temperature, °K	P Total pressure, dyne cm ⁻²	N Total concentration, cm ⁻³	T Kinetic temperature, °K	P Total pressure, dyne cm ⁻²	N Total concentration, cm ⁻³
	Ground air temperature T ₀ : 180°K			Ground air temperature T ₀ : 200°K		
0.000E-38	0.180000E 03	0.150000E 05	0.603664E 18	0.200000E 03	0.150000E 05	0.543297E 18
0.100E 06	0.178519E 03	0.135726E 05	0.550753E 18	0.194885E 03	0.136871E 05	0.508757E 18
0.200E 06	0.178439E 03	0.122847E 05	0.498713E 18	0.192771E 03	0.124765E 05	0.468844E 18
0.300E 06	0.178359E 03	0.111185E 05	0.451571E 18	0.192371E 03	0.113753E 05	0.428350E 18
0.400E 06	0.178279E 03	0.100625E 05	0.408867E 18	0.191971E 03	0.103692E 05	0.391280E 18
0.500E 06	0.178199E 03	0.910638E 04	0.370184E 18	0.191571E 03	0.945033E 04	0.357350E 18
0.600E 06	0.178119E 03	0.824078E 04	0.335147E 18	0.191171E 03	0.861119E 04	0.326301E 18
0.700E 06	0.178039E 03	0.745711E 04	0.303412E 18	0.190771E 03	0.784504E 04	0.297893E 18
0.800E 06	0.177959E 03	0.674766E 04	0.274669E 18	0.190371E 03	0.714566E 04	0.271906E 18
0.900E 06	0.177879E 03	0.610544E 04	0.248639E 18	0.189971E 03	0.650735E 04	0.248138E 18
0.100E 07	0.177799E 03	0.552408E 04	0.225065E 18	0.189571E 03	0.592489E 04	0.226405E 18
0.150E 07	0.177399E 03	0.334723E 04	0.136682E 18	0.187571E 03	0.369626E 04	0.142749E 18
0.200E 07	0.176999E 03	0.202591E 04	0.829135E 17	0.185571E 03	0.229429E 04	0.895603E 17
0.250E 07	0.176599E 03	0.122479E 04	0.502399E 17	0.183571E 03	0.141674E 04	0.559066E 17
0.300E 07	0.176199E 03	0.739612E 03	0.304073E 17	0.181571E 03	0.870239E 03	0.347192E 17
0.350E 07	0.175799E 03	0.446119E 03	0.183828E 17	0.179571E 03	0.531670E 03	0.214478E 17
0.400E 07	0.175399E 03	0.268781E 03	0.111006E 17	0.177571E 03	0.323035E 03	0.131782E 17
0.450E 07	0.174999E 03	0.161750E 03	0.669553E 16	0.175571E 03	0.195166E 03	0.805248E 16
0.500E 07	0.174599E 03	0.972261E 02	0.403383E 16	0.173571E 03	0.117234E 03	0.489276E 16
0.550E 07	0.171000E 03	0.587819E 02	0.249014E 16	0.171000E 03	0.708786E 02	0.300258E 16
0.600E 07	0.167000E 03	0.381182E 02	0.152332E 16	0.167000E 03	0.423451E 02	0.183680E 16
0.650E 07	0.163000E 03	0.207203E 02	0.920841E 15	0.163000E 03	0.249843E 02	0.111034E 16
0.700E 07	0.159000E 03	0.120661E 02	0.549726E 15	0.159000E 03	0.145492E 02	0.662853E 15
0.750E 07	0.155000E 03	0.693034E 01	0.323891E 15	0.155000E 03	0.835652E 01	0.390544E 15
0.800E 07	0.155000E 03	0.397688E 01	0.185861E 15	0.155000E 03	0.479528E 01	0.224109E 15
0.850E 07	0.155000E 03	0.228208E 01	0.106654E 15	0.155000E 03	0.275171E 01	0.128602E 15
0.900E 07	0.155000E 03	0.130954E 01	0.612018E 14	0.155000E 03	0.157903E 01	0.737964E 14
	Ground air temperature T ₀ : 190°K			Ground air temperature T ₀ : 210°K		
0.000E-38	0.190000E 03	0.150000E 05	0.571892E 18	0.210000E 03	0.150000E 05	0.517426E 18
0.100E 06	0.185730E 03	0.136247E 05	0.531399E 18	0.204938E 03	0.137479E 05	0.485953E 18
0.200E 06	0.185490E 03	0.123791E 05	0.483443E 18	0.200280E 03	0.125745E 05	0.454811E 18
0.300E 06	0.185250E 03	0.112460E 05	0.439761E 18	0.199720E 03	0.115041E 05	0.417259E 18
0.400E 06	0.185010E 03	0.102153E 05	0.399977E 18	0.199160E 03	0.105221E 05	0.382715E 18
0.500E 06	0.184770E 03	0.927799E 04	0.363747E 18	0.198600E 03	0.962150E 04	0.350946E 18
0.600E 06	0.184530E 03	0.842560E 04	0.330758E 18	0.198040E 03	0.879578E 04	0.321755E 18
0.700E 06	0.184290E 03	0.765055E 04	0.300724E 18	0.197480E 03	0.803888E 04	0.294882E 18
0.800E 06	0.184050E 03	0.694593E 04	0.273383E 18	0.196920E 03	0.734524E 04	0.270204E 18
0.900E 06	0.183810E 03	0.630541E 04	0.248497E 18	0.196360E 03	0.670972E 04	0.247530E 18
0.100E 07	0.183570E 03	0.572323E 04	0.225848E 18	0.195800E 03	0.612761E 04	0.226702E 18
0.150E 07	0.182370E 03	0.351927E 04	0.139790E 18	0.193000E 03	0.387719E 04	0.145524E 18
0.200E 07	0.181170E 03	0.215709E 04	0.862501E 17	0.190200E 03	0.243690E 04	0.928119E 17
0.250E 07	0.179970E 03	0.131787E 04	0.530457E 17	0.187400E 03	0.152113E 04	0.587996E 17
0.300E 07	0.178770E 03	0.802501E 03	0.325183E 17	0.184600E 03	0.942793E 03	0.369965E 17
0.350E 07	0.177570E 03	0.487043E 03	0.198689E 17	0.181800E 03	0.580082E 03	0.231138E 17
0.400E 07	0.176370E 03	0.294590E 03	0.120996E 17	0.179000E 03	0.354233E 03	0.143355E 17
0.450E 07	0.175170E 03	0.177573E 03	0.734336E 16	0.176200E 03	0.214640E 03	0.882432E 16
0.500E 07	0.173970E 03	0.106666E 03	0.444150E 16	0.173400E 03	0.129017E 03	0.538983E 16
0.550E 07	0.171000E 03	0.644894E 02	0.273192E 16	0.171000E 03	0.780025E 02	0.330437E 16
0.600E 07	0.167000E 03	0.385280E 02	0.167123E 16	0.167000E 03	0.466012E 02	0.202142E 16
0.650E 07	0.163000E 03	0.227322E 02	0.101025E 16	0.163000E 03	0.274955E 02	0.122194E 16
0.700E 07	0.159000E 03	0.132377E 02	0.603102E 15	0.159000E 03	0.160115E 02	0.729476E 15
0.750E 07	0.155000E 03	0.760324E 01	0.355339E 15	0.155000E 03	0.919643E 01	0.429797E 15
0.800E 07	0.155000E 03	0.436302E 01	0.203907E 15	0.155000E 03	0.527725E 01	0.246634E 15
0.850E 07	0.155000E 03	0.250366E 01	0.117009E 15	0.155000E 03	0.302828E 01	0.141527E 15
0.900E 07	0.155000E 03	0.143669E 01	0.671442E 14	0.155000E 03	0.173774E 01	0.812136E 14

Fig. 8. Lower Atmosphere Model III for ground air temperatures 180, 190, 200, and 210°K. Surface pressure 15 mb (0.15×10^5 dyne cm⁻²); atmospheric abundance 60% CO₂, 20% Ar, 20% N₂ by volume; mean molecular mass of atmospheric constituents 0.663921×10^{-22} gm.

H Height above mean surface, cm	Atmospheric parameters			Atmospheric parameters		
	T Kinetic temperature, °K	P Total pressure, dyne cm ⁻²	N Total concentration, cm ⁻³	T Kinetic temperature, °K	P Total pressure, dyne cm ⁻²	N Total concentration, cm ⁻³
	Ground air temperature T ₀ : 220°K			Ground air temperature T ₀ : 240°K		
0.000E-38	0.220000E 03	0.150000E 05	0.493907E 18	0.240000E 03	0.150000E 05	0.452748E 18
0.100E 06	0.214984E 03	0.138032E 05	0.465103E 18	0.235080E 03	0.139004E 05	0.428340E 18
0.200E 06	0.209969E 03	0.126770E 05	0.437359E 18	0.230160E 03	0.128607E 05	0.404774E 18
0.300E 06	0.207296E 03	0.116307E 05	0.406435E 18	0.225240E 03	0.118788E 05	0.382037E 18
0.400E 06	0.206576E 03	0.106724E 05	0.374245E 18	0.222083E 03	0.109607E 05	0.357520E 18
0.500E 06	0.205856E 03	0.979003E 04	0.344506E 18	0.221043E 03	0.101149E 05	0.331481E 18
0.600E 06	0.205136E 03	0.897794E 04	0.317037E 18	0.220003E 03	0.933071E 04	0.307229E 18
0.700E 06	0.204416E 03	0.823070E 04	0.291674E 18	0.218963E 03	0.860406E 04	0.284648E 18
0.800E 06	0.203696E 03	0.754334E 04	0.268261E 18	0.217923E 03	0.793094E 04	0.263632E 18
0.900E 06	0.202976E 03	0.691125E 04	0.246654E 18	0.216883E 03	0.730764E 04	0.244077E 18
0.100E 07	0.202256E 03	0.633016E 04	0.226720E 18	0.215843E 03	0.673067E 04	0.225890E 18
0.150E 07	0.198656E 03	0.406110E 04	0.148087E 18	0.210643E 03	0.443448E 04	0.152501E 18
0.200E 07	0.195056E 03	0.258433E 04	0.959763E 17	0.205443E 03	0.289133E 04	0.101949E 18
0.250E 07	0.191456E 03	0.163078E 04	0.617023E 17	0.200243E 03	0.186462E 04	0.674541E 17
0.300E 07	0.187856E 03	0.102011E 04	0.393366E 17	0.195043E 03	0.118869E 04	0.441484E 17
0.350E 07	0.184256E 03	0.632346E 03	0.248605E 17	0.189843E 03	0.748627E 03	0.285638E 17
0.400E 07	0.180656E 03	0.388298E 03	0.155700E 17	0.184643E 03	0.465462E 03	0.182611E 17
0.450E 07	0.177056E 03	0.236109E 03	0.966003E 16	0.179443E 03	0.285500E 03	0.115254E 17
0.500E 07	0.173456E 03	0.142109E 03	0.593484E 16	0.174243E 03	0.172618E 03	0.717640E 16
0.550E 07	0.171000E 03	0.859178E 02	0.363968E 16	0.171000E 03	0.104363E 03	0.442107E 16
0.600E 07	0.167000E 03	0.513300E 02	0.222654E 16	0.167000E 03	0.623498E 02	0.270455E 16
0.650E 07	0.163000E 03	0.302856E 02	0.134594E 16	0.163000E 03	0.367874E 02	0.163489E 16
0.700E 07	0.159000E 03	0.176363E 02	0.803500E 15	0.159000E 03	0.214225E 02	0.975999E 15
0.750E 07	0.155000E 03	0.101296E 02	0.473411E 15	0.155000E 03	0.123043E 02	0.575046E 15
0.800E 07	0.155000E 03	0.581276E 01	0.271661E 15	0.155000E 03	0.706068E 01	0.329982E 15
0.850E 07	0.155000E 03	0.333558E 01	0.155889E 15	0.155000E 03	0.405168E 01	0.189356E 15
0.900E 07	0.155000E 03	0.191408E 01	0.894548E 14	0.155000E 03	0.232500E 01	0.108659E 15
	Ground air temperature T ₀ : 230°K			Ground air temperature T ₀ : 250°K		
0.000E-38	0.230000E 03	0.150000E 05	0.472432E 18	0.250000E 03	0.150000E 05	0.434638E 18
0.100E 06	0.225033E 03	0.138539E 05	0.445966E 18	0.245126E 03	0.139433E 05	0.412653E 18
0.200E 06	0.220065E 03	0.127726E 05	0.420442E 18	0.240252E 03	0.129421E 05	0.390224E 18
0.300E 06	0.215098E 03	0.117540E 05	0.395845E 18	0.235379E 03	0.119945E 05	0.369139E 18
0.400E 06	0.214218E 03	0.108189E 05	0.365850E 18	0.230505E 03	0.110985E 05	0.348787E 18
0.500E 06	0.213338E 03	0.995477E 04	0.338018E 18	0.228971E 03	0.102696E 05	0.324909E 18
0.600E 06	0.212458E 03	0.915654E 04	0.312201E 18	0.227771E 03	0.949977E 04	0.302128E 18
0.700E 06	0.211578E 03	0.841939E 04	0.288262E 18	0.226571E 03	0.878403E 04	0.280844E 18
0.800E 06	0.210698E 03	0.773887E 04	0.266069E 18	0.225371E 03	0.811883E 04	0.260959E 18
0.900E 06	0.209818E 03	0.711085E 04	0.245502E 18	0.224171E 03	0.750086E 04	0.242386E 18
0.100E 07	0.208938E 03	0.653148E 04	0.226449E 18	0.222971E 03	0.692698E 04	0.225046E 18
0.150E 07	0.204538E 03	0.424713E 04	0.150418E 18	0.216971E 03	0.462241E 04	0.154327E 18
0.200E 07	0.200138E 03	0.273600E 04	0.990291E 17	0.210971E 03	0.304977E 04	0.104718E 18
0.250E 07	0.195738E 03	0.174538E 04	0.645938E 17	0.204971E 03	0.198817E 04	0.702648E 17
0.300E 07	0.191338E 03	0.110211E 04	0.417253E 17	0.198971E 03	0.127974E 04	0.465915E 17
0.350E 07	0.186938E 03	0.688516E 03	0.266805E 17	0.192971E 03	0.812695E 03	0.305079E 17
0.400E 07	0.182538E 03	0.425341E 03	0.168796E 17	0.186971E 03	0.508751E 03	0.197110E 17
0.450E 07	0.178138E 03	0.259691E 03	0.105603E 17	0.180971E 03	0.313652E 03	0.125550E 17
0.500E 07	0.173738E 03	0.156609E 03	0.652977E 16	0.174971E 03	0.190243E 03	0.787623E 16
0.550E 07	0.171000E 03	0.946841E 02	0.401104E 16	0.171000E 03	0.115013E 03	0.487247E 16
0.600E 07	0.167000E 03	0.565672E 02	0.245372E 16	0.167000E 03	0.687159E 02	0.298069E 16
0.650E 07	0.163000E 03	0.333756E 02	0.148326E 16	0.163000E 03	0.405435E 02	0.180181E 16
0.700E 07	0.159000E 03	0.194357E 02	0.885481E 15	0.159000E 03	0.236098E 02	0.107565E 16
0.750E 07	0.155000E 03	0.111632E 02	0.521713E 15	0.155000E 03	0.135606E 02	0.633759E 15
0.800E 07	0.155000E 03	0.640584E 01	0.299378E 15	0.155000E 03	0.778159E 01	0.363674E 15
0.850E 07	0.155000E 03	0.367591E 01	0.171794E 15	0.155000E 03	0.446536E 01	0.208690E 15
0.900E 07	0.155000E 03	0.210937E 01	0.985819E 14	0.155000E 03	0.256239E 01	0.119754E 15

Fig. 9. Lower Atmosphere Model III for ground air temperatures 220, 230, 240, and 250°K. Surface pressure 15 mb (0.15×10^5 dyne cm⁻²); atmospheric abundance 60% CO₂, 20% Ar, 20% N₂ by volume; mean molecular mass of atmospheric constituents 0.663921×10^{-22} gm.

H Height above mean surface, cm	Atmospheric parameters			Atmospheric parameters		
	T Kinetic temperature, °K	P Total pressure, dyne cm ⁻²	N Total concentration, cm ⁻³	T Kinetic temperature, °K	P Total pressure, dyne cm ⁻²	N Total concentration, cm ⁻³
	Ground air temperature T ₀ : 270°K			Ground air temperature T ₀ : 290°K		
0.000E-38	0.270000E 03	0.150000E 05	0.402442E 18	0.290000E 03	0.150000E 05	0.374688E 18
0.100E 06	0.265216E 03	0.140198E 05	0.382930E 18	0.285303E 03	0.140860E 05	0.357650E 18
0.200E 06	0.260433E 03	0.130876E 05	0.364034E 18	0.280607E 03	0.132139E 05	0.341123E 18
0.300E 06	0.255649E 03	0.122018E 05	0.345746E 18	0.275910E 03	0.123825E 05	0.325100E 18
0.400E 06	0.250866E 03	0.113609E 05	0.328057E 18	0.271213E 03	0.115904E 05	0.309573E 18
0.500E 06	0.246082E 03	0.105635E 05	0.310958E 18	0.266517E 03	0.108365E 05	0.294537E 18
0.600E 06	0.243969E 03	0.982068E 04	0.291597E 18	0.261820E 03	0.101195E 05	0.279983E 18
0.700E 06	0.242449E 03	0.912779E 04	0.272723E 18	0.259201E 03	0.944776E 04	0.264039E 18
0.800E 06	0.240929E 03	0.847988E 04	0.254963E 18	0.257361E 03	0.881875E 04	0.248222E 18
0.900E 06	0.239409E 03	0.787429E 04	0.238258E 18	0.255521E 03	0.822755E 04	0.233249E 18
0.100E 07	0.237889E 03	0.730850E 04	0.222551E 18	0.253681E 03	0.767214E 04	0.219081E 18
0.150E 07	0.230289E 03	0.499739E 04	0.157198E 18	0.244481E 03	0.536741E 04	0.159036E 18
0.200E 07	0.222689E 03	0.337379E 04	0.109748E 18	0.235281E 03	0.370391E 04	0.114038E 18
0.250E 07	0.215089E 03	0.224682E 04	0.756705E 17	0.226081E 03	0.251843E 04	0.806941E 17
0.300E 07	0.207489E 03	0.147457E 04	0.514811E 17	0.216881E 03	0.168515E 04	0.562850E 17
0.350E 07	0.199889E 03	0.952660E 03	0.345243E 17	0.207681E 03	0.110811E 04	0.386511E 17
0.400E 07	0.192289E 03	0.605138E 03	0.227969E 17	0.198481E 03	0.714951E 03	0.260935E 17
0.450E 07	0.184689E 03	0.377418E 03	0.148033E 17	0.189281E 03	0.451789E 03	0.172904E 17
0.500E 07	0.177089E 03	0.230767E 03	0.943970E 16	0.180081E 03	0.279037E 03	0.112246E 17
0.550E 07	0.171000E 03	0.139519E 03	0.591037E 16	0.171000E 03	0.168703E 03	0.714666E 16
0.600E 07	0.167000E 03	0.833532E 02	0.361562E 16	0.167000E 03	0.100788E 03	0.437190E 16
0.650E 07	0.163000E 03	0.491798E 02	0.218562E 16	0.163000E 03	0.594669E 02	0.264280E 16
0.700E 07	0.159000E 03	0.286390E 02	0.130478E 16	0.159000E 03	0.346295E 02	0.157770E 16
0.750E 07	0.155000E 03	0.164492E 02	0.768758E 15	0.155000E 03	0.198899E 02	0.929561E 15
0.800E 07	0.155000E 03	0.943916E 01	0.441142E 15	0.155000E 03	0.114136E 02	0.533416E 15
0.850E 07	0.155000E 03	0.541654E 01	0.253143E 15	0.155000E 03	0.654953E 01	0.306094E 15
0.900E 07	0.155000E 03	0.310821E 01	0.145263E 15	0.155000E 03	0.375836E 01	1.175648E 15

Fig. 10. Lower Atmosphere Model III for ground air temperatures 270 and 290°K. Surface pressure 15 mb (0.15×10^5 dyne cm⁻²); atmospheric abundance 60% CO₂, 20% Ar, 20% N₂ by volume; mean molecular mass of atmospheric constituents 0.663921×10^{-22} gm.

Author	Class of model	T_0 Ground air temperature, °K	Main constituents of lower atmosphere	P_0 Surface pressure, mb	T_{meso} Temperature at mesosphere base, °K	h_{meso} Altitude of mesosphere base, km	g/c_p Adiabatic temperature gradient, °K/km
Neubauer, 1966	Convective	~250	CO ₂ , N ₂	-	-	-	-
Anderson, 1965	Convective-radiative	175-325	CO ₂ , Ar	5.55	-	-	4.7-5.7
Leovy, 1966	Convective-radiative	225	CO ₂	5	-	-	3.5
Ohring et al., 1967	Convective-radiative	148-260	CO ₂ , N ₂	5-14	145-165	~25	4.35
Gierasch and Goody, 1967	Radiative	150-280	CO ₂	4.9	155	50	5

Fig. 11. Table of contemporary models for lower atmosphere of Mars.

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SECTION 5.4

UPPER ATMOSPHERE

This section has not been revised, although it contains outdated information written almost 5 years ago. However, the improved information on the Martian atmosphere obtained over the past 5 years is so substantial that a major research effort is required to evaluate and document this data properly.

The level of sophistication now possible in producing models from this later data should provide extremely meaningful information in the near future.

The material contained in this section can be utilized as background information.

Until the later data has been documented, reference to the Viking 75 Project, Mars Engineering Model (M75-125-1) will provide the reader with improved information.

5.4 UPPER ATMOSPHERE

DATA SUMMARY

Interpretation of the data from the Mariner IV occultation experiment has led to development of three distinct types of models for the upper atmosphere of Mars: a preliminary E-Model, an F_1 -Model at maximum solar flux (Figs. 1 through 5), and an F_2 -Model at minimum solar flux (Figs. 6 through 8).^{1*} In addition to occultation data, each of the models uses the best results of Earth-based observations, which are presented elsewhere in this document.²

The E-, F_1 -, and F_2 -Models are distinguished by the type of Earth-analog ionospheric layer which the ionized layer detected in the Martian atmosphere is thought to represent; they thus differ primarily in the structure of the ionosphere as derived from the physical and chemical processes thought to occur there. The "correct" choice among the models is not clear. The basic point of disagreement is proper identification of the concentration peak of the electron density profile measured at an altitude of approximately 120 km above Electris at the time of immersion of Mariner IV's S-band transmission on July 15, 1965.

DISCUSSION

Layers of the Upper Atmosphere

Using terrestrial nomenclature for classifying various regions of the atmosphere, the thermosphere is the highest region of the atmosphere where collisional interactions are still important, a region where kinetic temperature increases from its lowest value to a constant (which is quite high in the terrestrial case). The thermosphere differs from lower atmospheric levels because ionization and dissociation occur and diffusion becomes more important than mixing. The ionization region, or ionosphere, and dissociation region lie largely in the thermosphere. Both are produced primarily by interactions (photoionization and photodissociation) of extreme ultraviolet solar photons with atmospheric gases.

At some level in every atmosphere, called the critical level, the horizontal mean free path of neutral particles becomes equal to the density scale height. This critical level marks the base of the exosphere. In the exosphere, particles move along ballistic trajectories to a first approximation. If a magnetic field is present, it will fill a volume known as the magnetosphere, which generally extends beyond the exosphere and which must be considered in terms of its effects on charged-particle trajectories. The exosphere or magnetosphere is the region whose conditions determine the probability of escape of an atmospheric constituent.³

*See page 20 for list of cross references.

A planet without a permanent magnetic field may have a weak field convected into it by the solar wind. This, it is thought, would add to the formation of a collisionless bow shock in the solar wind ahead of and extending around the planet. Solar wind flow in the zone behind the shock offers a further factor affecting the exosphere. Attempts to account for this feature in relation to the Martian atmosphere are still in early stages and are not included in the atmospheric models presented in this section. (For additional reading about upper atmospheres, see Craig, 1965, and Fleagle and Businger, 1963).

Physics of the Upper Atmosphere

The important photochemical and physical processes which are believed to occur in the upper atmosphere of Mars are based upon the theories of photochemical and diffusive equilibrium in a quasi-stationary (approximately steady-state) atmosphere. These processes form the basis of the models presented in this section. The only available direct measurements of the properties of and processes occurring in the upper Martian atmosphere were provided by the 1965 Mariner IV occultation experiment.

Photodissociation Region

The photodissociative solar flux at a given height depends upon how much attenuation of the flux has taken place above the given level. The primary constituent that is photodissociated on Mars is CO_2 . The significant reactions occurring are



where M is any third body in the three-body process, and $h\nu$ is the energy of the incident photon.

Absorption of the solar spectrum between 1800 and 2400 Å by CO_2 and O_2 is negligible (Norton, 1964). Rayleigh (molecular) scattering of extreme ultraviolet solar photons with wavelengths lying between 1800 and 2400 Å is quite small. The optical depth for Rayleigh scattering at $\lambda 2100$ at the surface of Mars for a pure CO_2 atmosphere is less than 0.5 and decreases as the height increases because there are fewer and fewer molecules to scatter the radiation (Coulson and Lotman, 1962). This radiation is therefore able to penetrate to a lower level, where it is available to be absorbed by ozone, if any ozone exists. There will be some modification in detail if nitrogen exists in significant quantities.

When atomic oxygen is released from photodissociation of CO_2 , it is available for the oxidation of CO. The atomic oxygen may react with molecular oxygen through a third body to produce ozone.⁴ Ozone could then disappear by absorption of the extreme ultraviolet solar radiation. In fact, there is good evidence that there is little ozone present and that a great deal of ultraviolet radiation penetrates to the Martian surface.¹

To establish the major chemical processes important in the photodissociation region, the reaction rates of Eqs. (1) through (6) must be known. Two reactions produce CO_2 , one by two-body association (Eq. 2) and the other by three-body association (Eq. 6). At the densities and temperatures of the Martian atmosphere, two-body association dominates (Smith and Beutler, 1967). Both two-body (Eq. 4) and three-body (Eq. 3) association of O_2 must be considered, as the rates are comparable (Smith and Beutler, 1967).

At 90 and 100 km the concentrations of CO, O_2 , and O in the F_1 -Model are given (Fig. 1) by photochemical equilibrium calculations based upon the reactions given by Eqs. (1) through (6). These were modified between 100 and 110 km by estimating the effect of the transport terms in the continuity equation (diffusion) to improve the values of the concentrations. From 110 km up to the critical level (the base of the exosphere) at about 500 km, the various atmospheric species are thought to be in diffusive equilibrium as given by

$$[x] = [x]_{110 \text{ km}} \frac{T_{110 \text{ km}}}{T} \exp \left[- \frac{m}{k} \int_{110 \text{ km}}^h \frac{g}{T} dh \right] \quad (7)$$

where $[x]_{110 \text{ km}}$ and $T_{110 \text{ km}}$ are the concentration of any photodissociation product and the temperature, respectively, at a height of 110 km, m is the mean molecular mass, k is the Boltzmann constant, and g is the acceleration due to gravity.

Equation (7) is based upon the assumptions of hydrostatic equilibrium and the ideal equation of state and hence represents a diffusive distribution. Its applicability to the upper atmosphere of Mars to describe the concentration of various constituents as a function of altitude is valid even above the critical level, provided the deviation from hydrostatic equilibrium is small. Chamberlain (1963), in his monograph on the physics of planetary exospheres, tabulates the departure from hydrostatic equilibrium in terms of generally applicable atmospheric parameters. In the F_1 -Model of Smith and Beutler the critical level occurs at approximately 500 km based upon the mean free path between oxygen-oxygen collisions. Yet Chamberlain's work shows Eq. (7) to be applicable to an altitude of nearly 30,000 km if magnetospheric phenomena are ignored.

Ionosphere

One method of formation of an ionospheric layer, the classic Chapman layer, can be understood as follows. At large heights the density of any gas is very low and the corresponding rate of formation of electron-ion pairs is low.

At small heights the ultraviolet solar flux capable of ionizing a particular gas may be reduced by its passage through the atmosphere; hence, the rate at this height can also be low. At intermediate heights the formation rate of electron-ion pairs will reach a maximum since the product of density and ionizing flux reaches a maximum.

There are other ways to form a layer. In general, however, ionization of various species occurs throughout a thermosphere, with rather broad maxima being as likely as distinct layers. The Mariner IV occultation data indicated the presence of an ionized layer in the Martian atmosphere at an altitude of approximately 120 km (ingress).

Ionization Processes. The production rate of electrons and ions is in competition with the loss rate. The primary reactions for the production of electrons are



and



where X is the atom and X^+ the corresponding ion, XY is the molecule and XY^+ the corresponding ion. Production of ions is more complex than that of electrons as a result of the various chemical processes that can occur. Figure 9 gives the reactions that may occur significantly in the ionosphere of Mars for a pure CO_2 lower atmosphere and shows that the primary constituents of the Martian ionosphere are CO^+ , CO_2^+ , O^+ , O_2^+ , and electrons. Smith and Beutler (1967) derive the following equations for the concentrations of these constituents based upon chemical equilibrium:

$$[\text{CO}^+] = \frac{q_3[\text{CO}]}{k_1[\text{O}] + (k_3 + k_5)[\text{O}_2] + k_8[\text{CO}_2] + \alpha_3[e]} \quad (10)$$

$$[\text{CO}_2^+] = \frac{q_4[\text{CO}_2] + k_8[\text{CO}^+]}{(k_2 + k_7)[\text{O}] + k_6[\text{O}_2] + \alpha_4[e]} \quad (11)$$

$$[\text{O}^+] = \frac{q_1[\text{O}] + (k_1[\text{CO}^+] + k_2[\text{CO}_2^+])[\text{O}] + k_3[\text{CO}^+][\text{O}_2]}{k_4[\text{O}_2] + k_9[\text{CO}_2] + \alpha_1[e]} \quad (12)$$

$$[\text{O}_2^+] = \frac{q_2[\text{O}_2] + (k_4[\text{O}^+] + k_5[\text{CO}^+] + k_8[\text{CO}_2^+])[\text{O}_2] + k_7[\text{CO}_2^+][\text{O}]}{\alpha_2[e]} \quad (13)$$

Charge neutrality requires that

$$[e] = [CO^+] + [CO_2^+] + [O^+] + [O_2^+] \quad (14)$$

The q 's, α 's, and k 's in Eqs. (10) through (13) are rate coefficients for the various chemical processes appearing on the right side of Fig. 9.

The rate for photoionization q is not given explicitly in Fig. 9 but can be determined from Fig. 10. Values of the photoionization rate at a given altitude can be estimated by multiplying the extreme ultraviolet solar flux $J_o(\lambda)$ at the top of the Martian atmosphere by the cross section for photoabsorption $\sigma(\lambda)$ and by $e^{-\tau(\lambda)}$, where $\tau(\lambda)$ is the optical depth (at that altitude) at wavelength λ , to allow for absorption in higher atmospheric layers. The product $J_o(\lambda)\sigma(\lambda)e^{-\tau(\lambda)}$ is then integrated over λ for each constituent of the atmosphere.

To discuss the rate coefficients α and k it is necessary to simultaneously discuss the various chemical processes that can remove electrons and ions. The simplest process for loss of electrons and ions is the inverse of Eqs. (8) and (9), namely, radiative recombination.



A typical radiative recombination process which appears in Fig. 9 is



with a rate coefficient $\alpha_1 = 2 \times 10^{-12} \text{ cm}^3 \text{ sec}^{-1}$.

Nonradiative processes can remove electrons and ions much faster. If a molecular ion XY^+ recombines with an electron, the energy of recombination can dissociate the molecule into two atoms X and Y and will proceed with a far greater rate constant than processes involving photon emission.



Dissociative recombination is limited to the lower parts of the upper atmosphere because under diffusive equilibrium these molecules will tend to be concentrated lower in the atmosphere than lighter constituents such as atomic oxygen.

The ionization balance of atomic species must take account of charge transfer, that is,



and ion-atom (or molecule) exchange



which with Eq. (18) offer a vehicle for efficient removal of X^+ ions and electrons. A typical charge transfer reaction appearing in Fig. 9 is



with a rate coefficient $k_4 = 3.5 \times 10^{-11} \text{ cm}^3 \text{ sec}^{-1}$

In addition to the processes thus far mentioned, electron attachment can become important in the lower parts of the ionosphere.



where M is any third body. The negatively charged ion can combine with a positively charged ion to produce two neutral particles.



The total recombination rate coefficient, which includes radiative and dissociative recombination, must take account of dielectronic recombination. Dielectronic recombination represents the capture of an electron by an ion in a process which results in excitation of the resulting neutral into an upper quantum state. In the process the captured electron gives up some of its extra energy to one of the bound electrons. The result of dielectronic recombination is thus an atom or molecule with a doubly-excited state which then normally decays by ordinary photon emission.

Thermal Processes. The vertical temperature distribution and vertical temperature gradient of the Martian ionosphere is calculated from a detailed energy balance. The Martian ionosphere obtains its energy from the Sun and is expected to be in quasi-stationary equilibrium with the local UV photon flux at any given time of day.¹

A certain fraction of the solar radiant energy is reflected or absorbed directly by atmospheric gases or by clouds,⁵ and the remainder is absorbed or

reflected by the Martian surface.⁶ Of the energy absorbed by the Martian surface a large fraction is then reradiated in the infrared, where it can be absorbed by gases in the lower atmosphere. This energy trapping in the lower atmosphere constitutes a greenhouse effect which results in an increase of the surface temperature⁷ above the temperature for a corresponding atmosphere that is optically thin (transparent) at all wavelengths.

The extreme ultraviolet solar photons that are absorbed by the Martian atmospheric gases supply the energy required to maintain the thermosphere. The rate of thermal energy input into the thermosphere for each constituent is

$$E_j(h) = \int \epsilon_j(\lambda) \sigma_j(\lambda) N_j J_o(\lambda) e^{-\tau(\lambda)} d\lambda \quad (24)$$

where N_j represents the number density of constituent j and $\epsilon_j(\lambda)$ represents the efficiency for conversion of ultraviolet solar radiation to heat via photochemical processes by the j -th constituent; the other quantities have been defined previously. The total rate of heat input is the sum of E_j for all constituents; hence,

$$E(h) = \sum_j E_j(h) \quad (25)$$

The thermosphere of Mars is cooled by the rotational, vibrational, and electronic radiation of CO, CO₂, and O, respectively. The total rate of energy loss at each level of the thermosphere from the infrared radiation is

$$R(h) = \sum_j R_j(h) \quad (26)$$

where R_j represents the infrared radiative term for each constituent j . The only other mechanism considered significant in heat loss is thermal conduction. The thermal conductive flux is $AT^{1/2} dT/dh$ where $(AT^{1/2})$ is a weighted mean coefficient of thermal conductivity for CO₂, O₂, CO, and O.

The energy balance equation can now be written

$$\rho c_v \frac{\partial T}{\partial t} = \frac{\partial}{\partial h} \left(-AT^{1/2} \frac{\partial T}{\partial h} \right) + E(h) - R(h) \quad (27)$$

where ρ is total mass density of the gas, c_v is specific heat at constant volume, and $\partial T/\partial t$ is time rate of change of the kinetic temperature. Equation (27) is solved for quasi-stationary equilibrium ($\partial T/\partial t \approx 0$); hence,

$$AT^{1/2} \frac{dT}{dh} = \int_h^\infty (E - R) dh \quad (28)$$

Equation (28) determines the temperature gradient for the upper atmosphere of Mars. The temperature profile is then found by numerical integration using a previously derived lower atmosphere as the lower set of boundary conditions. Since $E(h)$, through $e^{-\tau(\lambda)}$, depends on the integrated atmosphere above h , an iterative procedure is necessary.

Contemporary Models of the Upper Atmosphere

Contemporary models of the upper Martian atmosphere are based on the general theory beginning on page 2 and ending above. They all use interpretations of data from the Mariner IV occultation experiment and the best results of Earth-based observations. The models are classified by approximate analogy to terrestrial ionospheric nomenclature as E-, F₁-, or F₂-(region) Models. Ionospheric regions or layers are differentiated by the wavelength of the radiation producing the region, by the principal ionic constituent, and by the dominant loss mechanism of ions and electrons.

The E-region of the Earth's atmosphere is produced primarily by x-rays from about 10 to about 100 Å assisted by some ultraviolet radiation from 800 to 1026 Å — particularly by emission lines such as Lyman β at 1025 Å (Craig, 1965). The most important ion produced is O₂⁺, and the loss mechanism is primarily dissociative recombination. This region is a fair approximation to the classic Chapman layer described briefly on page 3, a layer in which the peak electron density is approximately coincident with the peak of the electron production.

The terrestrial F-region is produced by extreme ultraviolet radiation in the wavelength range from 200 to 800 Å with some contribution from longer wavelengths. The principal ion present is O⁺ (Craig, 1965). The loss mechanism is ion-atom interchange up to a high level, where radiative recombination becomes dominant. This is a height-dependent process which results in the peak electron density being at a much higher altitude than the peak of production, a so-called Bradbury layer. Actually, the F-region contains two peaks: a lower layer called the F₁-layer near the production maximum, and the Bradbury layer peak called the F₂-peak (Craig, 1965).

Preliminary E-Model

In their preliminary paper, Chamberlain and McElroy (1966) interpret the ionization layer above Electris to be an E-region. They assume a composition of only 44% CO₂, the remainder being N₂. Their model relies heavily on the speculative assumption that mixing provides homogeneous composition of constituent gases throughout the entire upper atmosphere. They assume that the rate of photodissociation is so small that CO₂ will be only partially photodissociated, even at great heights, primarily because the rapid formation of O₂ (from O resulting from the CO₂ dissociation) shields the CO₂. They further assume a very large rate coefficient for dissociative recombination of CO₂⁺ to prevent formation of an F₁-region above the E-region (since of course none was observed). A new determination of this coefficient by Weller and Biondi (1967) makes it difficult to accept such an assumption.

These assumptions can result in an ionosphere dominated by O₂⁺ (or perhaps NO⁺)⁸ in a Chapman layer created primarily by x-rays.¹ With appropriate rate coefficients the layer is of the strength and at the height measured by

Mariner IV. Chamberlain and McElroy's assumptions seem questionable according to proponents of other models; in addition, they do not present the observed ionospheric scale height. However, Chamberlain and McElroy are working on much more detailed calculations, and a final E-Model will be added to this section when the results become available from these authors.

F₁-Model (Figs. 1 through 5)

This model is based upon the work of Smith and Beutler (1967), who have interpreted the ionization layer observed over Electris to be an F₁-region. It presents the largest reasonable values possible for density and kinetic temperatures above 90 km, without going to an E-type model, and utilizes maximum ultraviolet solar flux and the best available rate coefficients for photochemical and diffusive processes. (The model has been used to illustrate the discussion on pages 2 through 8.) More extreme models are possible if there are errors in current theories and/or constants.

The calculated neutral number densities and temperatures versus altitude for the F₁-Model are tabulated in Fig. 1. Figure 2 contains profiles of electron density and densities of the most abundant molecular and atomic ion species; the CO₂⁺ abundance is very small and therefore is not shown. Figures 3 and 4 respectively give profiles of temperature versus altitude and of neutral density versus altitude. Figure 5 shows the rate of photoionization of neutral atoms and molecules above an altitude of 90 km. Since production of electron-ion pairs by photoabsorption completely dominates other formation mechanisms, the figure thus represents total ion production rate, which in turn is based upon the rate of photoabsorption of extreme ultraviolet solar photons at sunspot maximum (Fig. 10).

The F₁-Model results in three ionization peaks characterized by F-type charge transfer loss processes. In the lower layers of the upper atmosphere the most abundant molecular ion is O₂⁺. Peak concentration of O₂⁺ is 37,000 particles cm⁻³ at an altitude of 160 km. The dominant ion in the upper, or F₂-type, layer is O⁺, which reaches a concentration of 8.8 × 10⁵ particles cm⁻³ at an altitude of 420 km. In fact, O⁺ is the most abundant atomic ion anywhere in the upper atmosphere of Mars.

The results of the Mariner IV occultation experiment as presented by Kliore et al. (1967) indicate that only one of these layers, the lowest, was detected; peak electron concentration (ingress) was 9.0 ± 1.0 × 10⁴ electrons cm⁻³ at an altitude of 123 ± 3 km. Smith and Beutler (1966) suggest that with low solar activity and at large solar zenith angle, as encountered by Mariner IV, the large upper peak (of the F₂-type) at 420 km will disappear. They further imply that the two lower peaks at 120 and 160 km will coalesce under these conditions into a single thin but rather dense O₂⁺ peak of the F₁-type, creating the peak observed by Mariner IV. In a brief paper that presents no detailed results, Donahue (1966) also interprets the ionization layer over Electris to be an F₁-region and comments that an F₂-layer can be suppressed if loss of O⁺ via the reaction



indeed has a rate coefficient of 1.2 × 10⁻⁹ cm³ sec⁻¹

At an altitude of 90 km, which is roughly the lower boundary of the thermosphere in the Smith and Beutler F_1 -Model, the kinetic temperature, total gas pressure, and concentration of CO_2 are taken from lower atmosphere Model I of Prabhakara and Hogan (1965).⁹ The concentration of CO_2 for Model I of Prabhakara and Hogan is changed from 44% to 100%. The assumptions used to generate the F_1 -Model of Smith and Beutler (1967) are listed below.

- 1) CO_2 is assumed to be the only significant constituent of the lower atmosphere. This is consistent with the results of Mariner IV data.
- 2) The atmosphere is assumed to be in a quasi-stationary equilibrium.
- 3) Advection, the horizontal transport of convective cells of matter, is considered negligible. Inclusion of horizontal transport would reduce the effectiveness of diffusion.
- 4) The solar extreme ultraviolet spectrum used to represent the dissociating and ionizing agent for the upper atmosphere is based on data from maximum solar activity (Fig. 10). If the spectrum were based on data from minimum solar activity, the flux contained in Fig. 10 would be smaller by a factor of approximately two (Ohring, 1967).
- 5) Mixing and eddy diffusion are assumed present in the lower atmosphere and represent the primary mechanism for the transport of photodissociation products to this region. With this assumption Smith and Beutler use the results of Prabhakara and Hogan (1965) to obtain the concentration of CO_2 and temperature at the base of the photodissociation region.
- 6) The primary mechanisms that establish the adopted temperature profile for the upper atmosphere of Mars are assumed to be heating due to absorption of the extreme ultraviolet solar radiation and subsequent cooling by radiation in the infrared and thermal conduction.
- 7) Both chemical and diffusive equilibrium are used to establish the particle concentration in the upper atmosphere.
- 8) The equation of state for the upper atmosphere and ionosphere of Mars is assumed ideal.
- 9) Gravity through the upper atmosphere is assumed to vary inversely with the square of the areocentric distance ($R_0 + h$).
- 10) Accretion or escape of CO_2 to the interplanetary medium is assumed negligible. This implies no net flux or transport of CO_2 other than the removal by photodissociation.
- 11) The magnetic field of Mars is assumed negligible. A magnetic field does not affect neutral constituents of an atmosphere. If the neutral constituents are in diffusive equilibrium, they will maintain this equilibrium with the injection of a magnetic field. On the other

hand, the molecular and atomic ions will be affected by lines of force and ultimately will be able to diffuse only along the magnetic lines of force. A magnetic field would lead to the probable development of weak radiation belts high in the upper atmosphere.³

- 12) Collisional dissociation and ionization by the solar wind is assumed negligible. During maximum solar activity the solar wind and extreme ultraviolet radiation will have comparable energy fluxes.
- 13) Aerosol concentration is considered negligible.
- 14) The model is derived for the subsolar region of the atmosphere.
- 15) Latitudinal and seasonal variations in the atmosphere are neglected.
- 16) Charge neutrality is assumed; hence, no residual electric fields exist.

F₂-Model (Figs. 6 through 8)

This model is based upon the work of Fjeldbo, Fjeldbo, and Eshleman (1966b), who have interpreted the ionization layer above Electris to be an F₂-region. It should be considered a limiting lower density model with the lowest reasonable exospheric temperature; it uses minimum extreme ultraviolet solar flux and the best available photochemical and diffusive constants. A more extreme model is conceivable only if there are errors in the current theories and/or constants.

The calculated neutral and electronic number densities and temperatures versus altitude for the F₂-Model are tabulated in Fig. 6. Figure 7 gives the calculated concentrations of [O], [CO], [CO₂], and [e] for the upper atmosphere, the base of which starts at roughly 90 km—the altitude for minimum temperature. Above this altitude [O] becomes the dominant constituent. Figure 8 gives the temperature profile above an altitude of 90 km. Above 135 km the temperature becomes isothermal at a value of 80°K.

The F₂-Model relies heavily on the assumption that loss of O⁺, which Fjeldbo et al. assume to be the principal constituent of the ionosphere, is governed by Eq. (29) with a rate coefficient of 10⁻⁹ cm³ sec⁻¹. The model does not include additional nonradiative processes such as those found in Fig. 9.

At an altitude of 120 km the electron concentration and kinetic temperature of the F₂-Model agree with the results from the Mariner IV occultation experiment (ingress), which also indicated that at the surface of Mars (Electris) the pressure was 4.9 to 5.2 mb, air temperature was 175 to 180°K, and concentration of CO₂ was 1.9 to 2.1 × 10¹⁷ particles cm⁻³ (Kliore et al., 1967). The model parameters are adjusted to match these data. Egress data over Mare Acidaliu indicated a surface pressure of 7.6 to 8.2 mb and a temperature of 235 to 240°K, but this information was not yet available when Fjeldbo et al. produced their model. Since this is presented as a limiting model, the lack of egress data is immaterial.¹⁰

The assumptions used to generate the F_2 -Model of Fjeldbo, Fjeldbo, and Eshleman (1966b) are as follows:

- 1) The lower atmosphere is assumed to be pure CO_2 .
- 2) The photochemistry assumed to be significant in the upper atmosphere is photodissociation of CO_2 and O_2 by the extreme ultraviolet solar radiation.
- 3) Three-body association is assumed to be the dominant mechanism for formation of O_2 and CO_2 .
- 4) Molecular diffusion is assumed to be the dominant physical process that establishes the concentration of constituents.
- 5) "Hard" corpuscular radiation is assumed to be a negligible ionizing agent.
- 6) The temperature profile represents an empirical fit to the data of the Mariner IV occultation experiment. No energy balance was assumed.
- 7) It is assumed that formation of dry ice (condensed CO_2) can occur near the base of the exosphere.
- 8) Aerosol concentration is assumed negligible.
- 9) The model is derived for local conditions over the occulting regions on Mars.
- 10) Latitudinal and seasonal variations in the atmosphere are neglected.
- 11) The magnetic field of Mars is assumed negligible.
- 12) The equation of state for the upper atmosphere is assumed ideal.
- 13) Gravity through the upper atmosphere is assumed to vary inversely with the square of the areocentric distance.
- 14) Charge neutrality is assumed; hence, no residual electric fields exist.

Johnson (1965) has also interpreted the ionization layer above Electris as an F_2 -region. The model of Johnson is an empirical model which uses the plasma scale height observed by Mariner IV and assumes that O^+ is the dominant ion in the upper atmosphere in order to derive an exospheric temperature of $85^\circ K$. The temperature distribution is not obtained from a detailed energy balance but is assumed to follow the vapor pressure curve for dry ice in the phase equilibrium diagram." This highly speculative assumption is not based upon calculated or observed results but represents the result of plausibility arguments. Fjeldbo et al. (1966a) compare all post-Mariner IV models in a good review of the subject.

CONCLUSIONS

Lacking detailed information, contemporary models tend to rely heavily on terrestrial analogy even though the differences in atmospheric composition between planets make such analogies of dubious value. For example, an F_1 ionization layer in the terrestrial atmosphere will generally appear more frequently near midday and in summer than near sunset or sunrise or in winter (Yonezawa, 1966). The reason for this is that the level at which the peak in the electron production profile occurs in the terrestrial atmosphere is a function of the solar zenith angle. Table VII of Yonezawa demonstrates that the altitude at which the peak in the electron production profile occurs increases as the solar zenith angle increases. If the altitude of the electron production peak lies below the altitude of the boundary that separates radiative and nonradiative removal processes, then an F_1 -region will appear. If the above conditions are not satisfied, then an F_1 -region will not form. The immersion data from Mariner IV occurred in winter with a solar zenith angle of 67° above Electris (Kliore et al., 1967).¹² Therefore, it would seem inappropriate to call the ionization layer observed over Electris an F_1 -layer even though it has some of the properties of such a layer.

All the models use photochemical and diffusive rate coefficients which are not well determined. The result of using various values for the rate coefficients that exist is to produce models that contain a great deal of uncertainty. With an inappropriate identification of the ionization layer that was observed by Mariner IV, and the ignoring of predicted layers not observed by the probe, plus the use of different rate coefficients, plus some "hand-waving," many models can be produced that will reproduce the Mariner IV data. Figure 11 outlines the models that are based on the results of Mariner IV. From the figure it is seen that there are great differences in atmospheric parameters among the various models. The E- and F_1 -Models show a high exospheric temperature while the F_2 -Models show a low exospheric temperature. The effort to build a model that correctly describes the Mariner IV occultation experiment has created more questions than answers about the structure of the upper atmosphere of Mars.

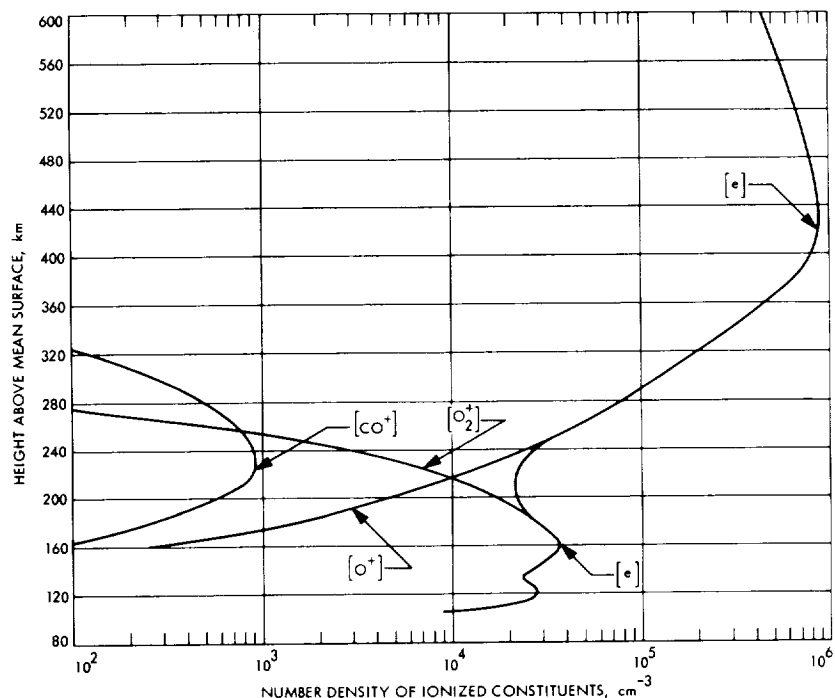
h Height above mean surface, ^a km	T Kinetic temperature of atmos- pheric constituents, °K	Concentration, ^b cm ⁻³				H(O) Density scale height for atomic oxygen, km
		[CO ₂]	[CO]	[O ₂]	[O]	
90	155	1.89 ¹³	1.16 ¹²	3.64 ¹¹	4.32 ¹¹	-
100	137	5.92 ¹²	1.82 ¹²	1.34 ¹¹	1.55 ¹²	-
110	132	1.47 ¹²	1.31 ¹²	2.22 ¹⁰	1.26 ¹²	-
120	135	3.70 ¹¹	5.28 ¹¹	3.58 ⁹	7.45 ¹¹	20.1
130	149	9.10 ¹⁰	2.08 ¹¹	5.00 ⁸	4.20 ¹¹	22.3
140	166	2.04 ¹⁰	8.97 ¹⁰	9.3 ⁷	2.48 ¹¹	24.9
160	200	2.88 ⁹	2.08 ¹⁰	2.4 ⁶	9.93 ¹⁰	30.4
200	327	1.13 ⁸	2.22 ⁹	1.6 ³	2.24 ¹⁰	50.9
240	415	1.37 ⁷	5.31 ⁸	-	8.94 ⁹	66.0
280	462	2.57 ⁶	1.77 ⁸	-	4.55 ⁹	75.1
320	488	6.10 ⁵	6.84 ⁷	-	2.57 ⁹	81.1
400	508	4.38 ⁴	1.26 ⁷	-	9.67 ⁸	88.1
480	514	3.70 ³	2.63 ⁶	-	3.92 ⁸	92.8
560	516	3.63 ²	6.00 ⁵	-	1.68 ⁸	97.2
640	520	-	-	-	9.25 ⁷	102.1
720	520	-	-	-	5.22 ⁷	106.1
800	520	-	-	-	3.00 ⁷	110.4
900	520	-	-	-	1.58 ⁷	115.6
1000	520	-	-	-	8.42 ⁶	121.3

^aSmith and Beutler (1967) <560 km; Monash >560 km including H(O) and [O] calculated from Eq. (7), page 3.

^bThe superscript in concentration values is the power of ten to which the value must be raised. For example, 1.89¹³ = 1.89 × 10¹³.

Fig. 1. Upper Atmosphere F₁-Model: table of calculated neutral number densities and temperatures vs. altitude. $H(O) = kT/\mu g = 5.20 \times 10^1 T/g$, where $g = g_0/(1 + h/R_0)^2$. T is in °K, g in cm sec⁻². $g_0 = 375$ cm sec⁻², and $R_0 = 3380$ km.

Fig. 2. Upper Atmosphere F₁-Model: ion and electron density vs. altitude. Note that below 200 km, the curve for electron concentration coincides with the O₂⁺ concentration curve. Above 240 km, the curve for electron concentration coincides with the O⁺ concentration curve.



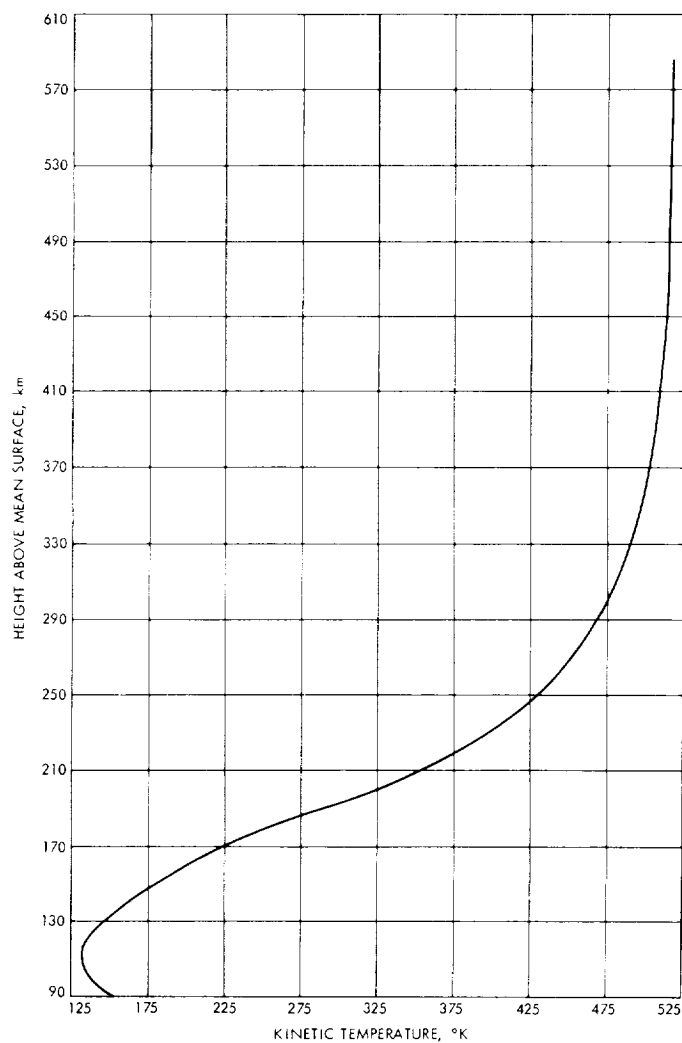


Fig. 3. Upper Atmosphere F₁-Model: temperature vs. altitude. This figure is a graph of the second column (Temperature) of Fig. 1; the same precautions that exist for Fig. 1 therefore apply.

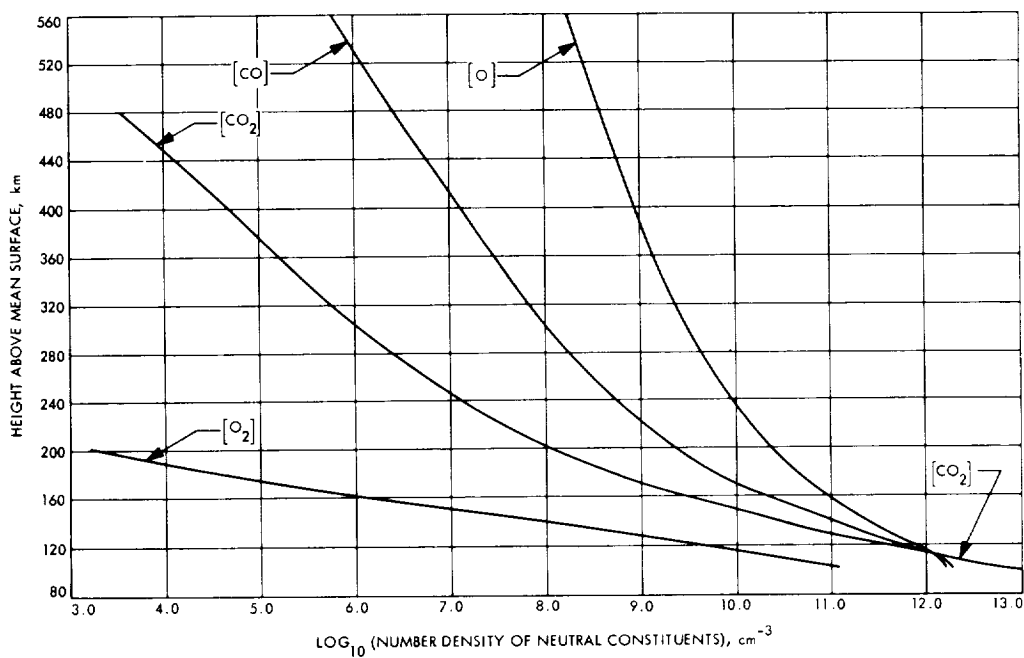


Fig. 4. Upper Atmosphere F₁-Model: neutral density vs. altitude. This figure is a graph of the third through sixth columns (Concentration) of Fig. 1; the same precautions that exist for Fig. 1 therefore apply.

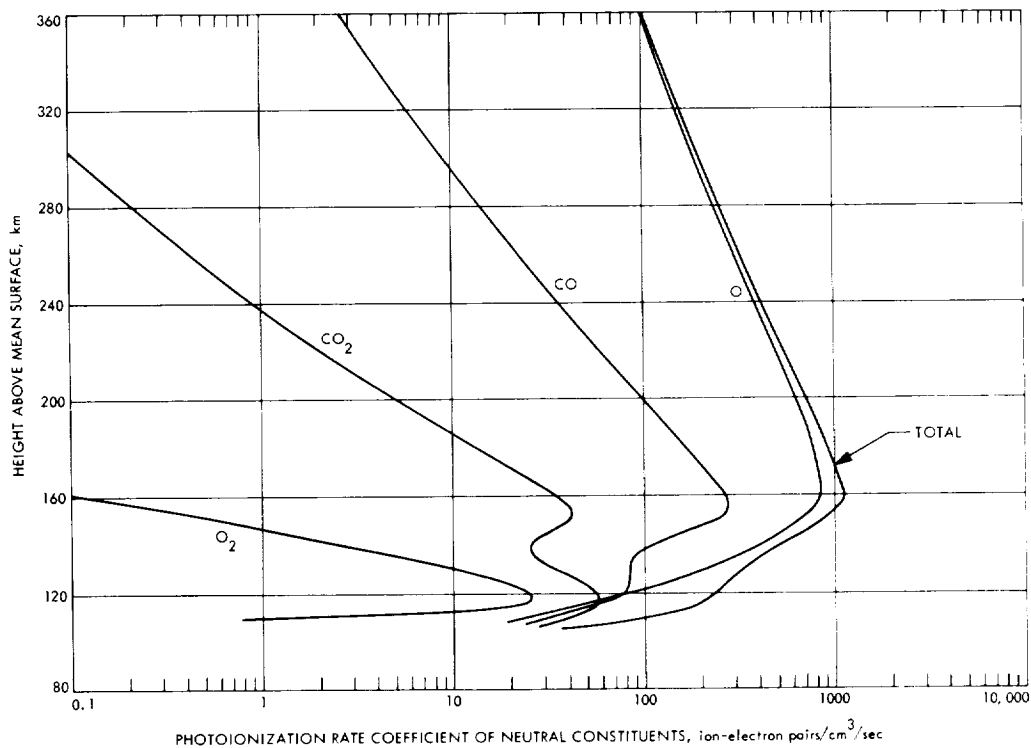


Fig. 5. Upper Atmosphere F₁-Model: profiles of photoionization rate of neutral constituents.

h Height above mean surface, km	T Kinetic temperature of atmos- pheric constituents, °K	Concentration, ^a cm ⁻³				H(O) Density scale height for atomic oxygen, km
		[CO ₂]	[O]	[CO]	[e]	
90	50	7.95 ¹⁰	5.01 ¹⁰	1.58 ¹⁰	-	7.31
100	51	1.26 ⁹	1.26 ¹⁰	1.78 ⁹	2.00 ⁴	7.49
110	60	5.63 ⁷	3.16 ⁶	1.78 ⁸	3.16 ⁴	8.87
120	70	3.16 ⁶	1.00 ⁵	2.00 ⁷	8.90 ⁴	10.4
130	78	2.00 ⁵	3.54 ⁵	3.54 ⁶	6.60 ⁴	11.7
140	80	-	1.41 ⁸	1.00 ⁶	4.78 ⁴	12.0
150	80	-	7.08 ⁷	-	3.32 ⁴	12.1
160	80	-	3.54 ⁷	-	2.34 ⁴	12.2
170	80	-	1.86 ⁷	-	1.58 ⁴	12.2
180	80	-	1.00 ⁷	-	1.00 ⁴	12.3
190	80	-	5.63 ⁶	-	-	12.4
200	80	-	3.54 ⁶	-	-	12.4

^aThe superscript in concentration values is the power of ten to which the value must be raised. For example, 7.95¹⁰ = 7.95 × 10¹⁰.

Fig. 6. Upper Atmosphere F₂-Model: table of calculated neutral and elec-
tronic number densities and tempera-
ture vs. altitude. $H(O) = kT/\mu g = 5.20 \times 10^1 T/g$, where $g = g_0/(1 + h/R_0)^2$.
 T is in °K, g in cm sec⁻². $g_0 = 375$
cm sec⁻², and $R_0 = 3380$ km.

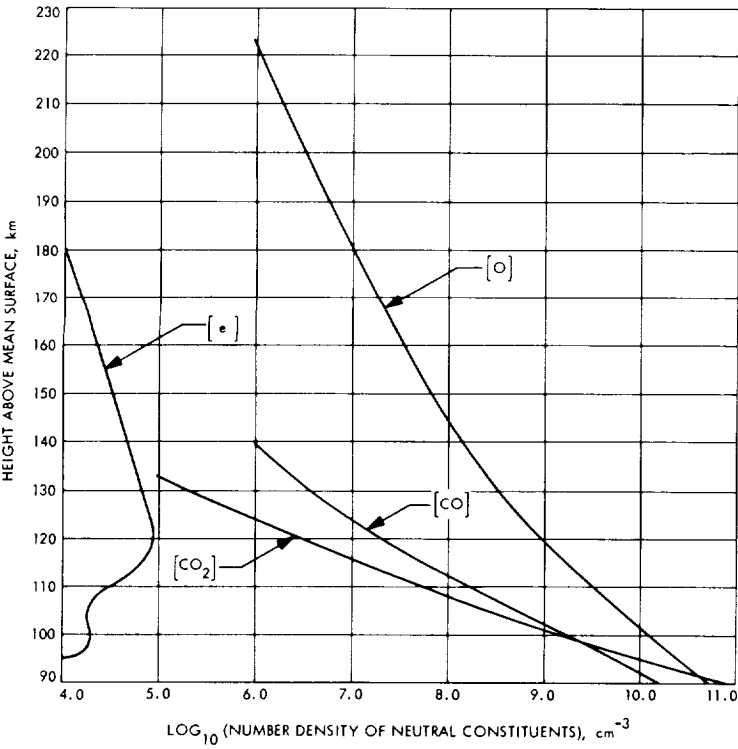


Fig. 7. Upper Atmosphere F₂-Model: number
density of electronic and neutral constituents
vs. altitude.

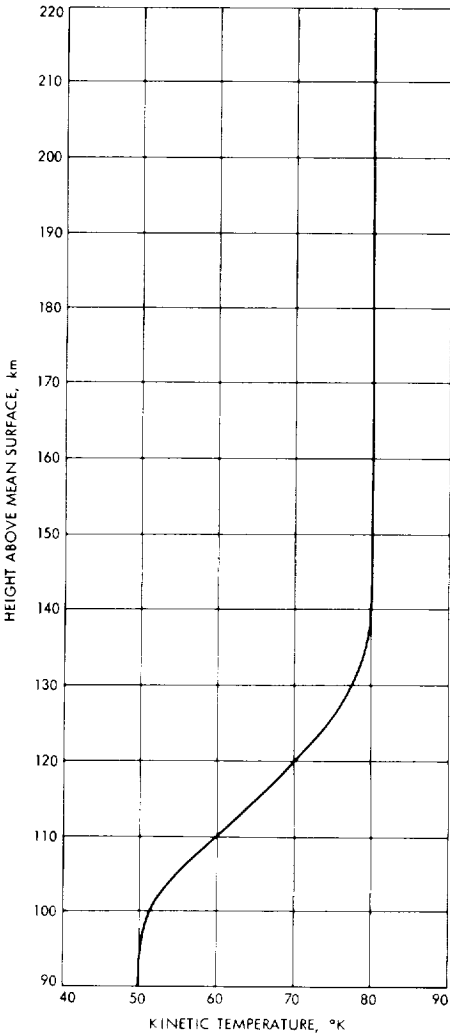


Fig. 8. Upper Atmosphere
F₂-Model: temperature vs.
altitude.

Reaction	Rate coefficient
$O + h\nu \rightarrow O^+ + e$	$q_1 \text{ sec}^{-1}$
$CO^+ + O \rightarrow O^+ + CO + 0.38 \text{ e.v.}$	$k_1 = 2 \times 10^{-12} \text{ cm}^3 \text{ sec}^{-1}$
$CO_2^+ + O \rightarrow O^+ + CO_2 + 0.16 \text{ e.v.}$	$k_2 = 2 \times 10^{-12} \text{ cm}^3 \text{ sec}^{-1}$
$CO^+ + O_2 \rightarrow O^+ + CO_2 + 0.73 \text{ e.v.}$	$k_3 = 1 \times 10^{-12} \text{ cm}^3 \text{ sec}^{-1}$
$O^+ + e \rightarrow O + h\nu$	$\alpha_1 = 2 \times 10^{-12} \text{ cm}^3 \text{ sec}^{-1}$
$O^+ + O_2 \rightarrow O_2^+ + O + 1.58 \text{ e.v.}$	$k_4 = 3.5 \times 10^{-11} \text{ cm}^3 \text{ sec}^{-1}$
$O_2 + h\nu \rightarrow O_2^+ + e$	$q_2 \text{ sec}^{-1}$
$CO^+ + O_2 \rightarrow O_2^+ + CO + 1.93 \text{ e.v.}$	$k_5 = 2 \times 10^{-10} \text{ cm}^3 \text{ sec}^{-1}$
$CO_2^+ + O_2 \rightarrow O_2^+ + CO_2 + 1.71 \text{ e.v.}$	$k_6 = 1 \times 10^{-10} \text{ cm}^3 \text{ sec}^{-1}$
$CO_2^+ + O \rightarrow O_2^+ + CO + 1.36 \text{ e.v.}$	$k_7 = 5 \times 10^{-11} \text{ cm}^3 \text{ sec}^{-1}$
$O_2^+ + e \rightarrow O + O + 6.92 \text{ e.v.}$	$\alpha_2 = 2 \times 10^{-7} \text{ cm}^3 \text{ sec}^{-1}$
$CO + h\nu \rightarrow CO^+ + e$	$q_3 \text{ sec}^{-1}$
$CO^+ + CO_2 \rightarrow CO_2^+ + CO + 0.22 \text{ e.v.}$	$k_8 = 1.1 \times 10^{-9} \text{ cm}^3 \text{ sec}^{-1}$
$CO^+ + e \rightarrow C + O + 2.85 \text{ e.v.}$	$\alpha_3 = 1 \times 10^{-7} \text{ cm}^3 \text{ sec}^{-1}$
$CO_2 + h\nu \rightarrow CO_2^+ + e$	$q_4 \text{ sec}^{-1}$
$O^+ + CO_2 \rightarrow O_2^+ + CO + 1.20 \text{ e.v.}$	$k_9 = 1.2 \times 10^{-9} \text{ cm}^3 \text{ sec}^{-1}$
$CO_2^+ + e \rightarrow CO + O + 8.23 \text{ e.v.}$	$\alpha_4 = 3 \times 10^{-7} \text{ cm}^3 \text{ sec}^{-1}$

Fig. 9. Table of significant reactions in the Martian ionosphere for a pure CO_2 lower atmosphere. (Smith and Beutler, 1967)

Fig. 10. Table of incident solar flux densities at Mars and absorption cross sections for selected wavelength regions. (Smith and Beutler, 1967)

Wavelength region, λ	Incident solar flux density, $\text{cm}^{-2} \text{ sec}^{-1}$		σ Absorption cross section, cm^2			
	J_0 Photons	S_0 Ergs	(O_2)	(CO_2)	(O)	(CO)
1800-1700	474×10^9	10.95	0.25×10^{-18}	0.0064×10^{-18}	-	-
1700-1600	358	4.28	2.0	0.0741	-	-
1600-1500	193	2.51	8.0	0.0432	-	-
1500-1400	164	2.74	0.5	1.88	-	-
1400-1300	6.44	0.131	0.5	17.5	-	-
1300-1200	5.33	0.0942	5.15	5.15	-	-
1200-1100	2.48	0.0434	7.28	7.28	2.69×10^{-18}	-
1100-1000	1.77	0.0543	10.17	12.90	3.05	12.90×10^{-18}
1000-900	5.88	0.382	17.00	12.34	8.80	12.34
900-800	1.06	0.123	6.61	5.71	3.30	5.71
800-700	0.276	0.0531	1.67	1.60	0.87	1.60
700-600	0.649	1.85	0.84	0.65	0.42	0.66

Author	Class of model	T _{ex} Exospheric temperature, K	Main constituents of upper atmosphere	Concentration per cm ³ at 100-km altitude			P ₀ Assumed surface pressure, mbar	h _{ex} Height of exosphere above surface, km
				[CO ₂]	[O]	[CO]		
Chamberlain and McElroy, 1966	E ₂ -region	<400	NO ⁺ or O ₂ ⁺	2×10^{13}	-	2×10^{12}	10	~300
Johnson, 1965	F ₂ -region	85	O ⁺	3×10^{10}	1×10^{10}	3×10^9	~4	100
Smith and Beutler, 1966	F ₁ -region	420	O ⁺	5×10^{11}	2×10^{11}	3×10^{11}	7	~600
Donahue, 1966	F ₁ -region	400	O ₂ ⁺	2×10^{12}	3×10^{10}	3×10^{10}	7	250
Einfeldt, Einfeldt, and Eshleman, 1966b	F ₂ -region	80	O ⁺	2×10^9	2×10^{10}	2×10^9	5	~140
Gross, McGovern, and Rasoul, 1966	"	550	O ⁺	-	-	-	8	~300
Smith and Beutler, 1967	F ₁ -region	520	O ⁺	5.92×10^{12}	1.55×10^{12}	1.82×10^{12}	10	560

Fig. 11. Table of models for upper atmosphere of Mars based on Mariner IV results.

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THE MAGNETIC, RADIATION, AND PARTICLE ENVIRONMENT OF MARS

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6. CIS-MARTIAN MEDIUM, RADIATION: THE MAGNETIC, RADIATION, AND PARTICLE ENVIRONMENT OF MARS

DATA SUMMARY (Sources are given in the Discussion.)

Total Irradiation

582.7 W m⁻² at mean solar distance
 709.0 W m⁻² at perihelion
 487.5 W m⁻² at aphelion

Solar Spectral Irradiance

The distribution of the Sun's power with wavelength is shown for ultra-violet, visible, and infrared light in Table 1, page 6. Extreme ultraviolet irradiance is given in Table 2, page 10. Data on x-rays and radio emission are contained in the body of the text.

Solar Wind

Detailed properties of the solar wind in the near-Mars and near-Earth regions are listed in Tables 3, 4, and 5, pages 14 and 15, respectively.

Energetic Particles

The maximum number of solar event protons reaching the Martian surface are given in Table 6, page 18.

Solar Interplanetary Magnetic Field

Strength at 1.5 AU, the mean distance of Mars from the Sun

Strength is dependent upon solar activity and may fluctuate 1 to 2 orders of magnitude.

Average

2 γ (1 γ = 10⁻⁵ gauss)

Range

0 to 25 γ

Magnetic Field at Mars

The following upper limits are based upon the apparent absence of a Martian shock wave or magnetosphere along the Mariner IV trajectory. The magnetic moment of the Earth = $M_E = 8.05 \pm 0.02 \times 10^{25}$ gauss cm³.

Martian magnetic moment, upper limit

$3 \times 10^{-4} M_E$

Surface magnetic field at equator, upper limit

100 γ

Piled-up interplanetary field $\sim 35\gamma$
at subsolar point (if internal
moment is zero)

Martian Meteoroid Environment

The terrestrial meteoroid mass-flux relationship is shown in Fig. 3, page 25. There are indications that the dust flux may be three to five times larger at Mars. There is no data on larger bodies. Mars will encounter meteoroids with relative velocities between 10 and 58 km sec⁻¹. See the main text for details.

DISCUSSION

Solar Electromagnetic Radiation

Total Electromagnetic Irradiation

By definition, the solar constant is the total electromagnetic irradiation per-unit-area normal to a solar radius vector, at a distance of one astronomical unit (AU) from the Sun and outside the Earth's atmosphere. Thus, it is a direct measure of the solar power output. At Mars' mean distance of 1.5237 AU from the Sun, the total electromagnetic irradiation is only 0.4307 of the solar constant, while at perihelion it is 0.5240 and at aphelion 0.3603.

For many years it was convenient to use Johnson's (1954) value of the solar constant, 2.00 cal cm⁻² min⁻¹ (1395 W m⁻²). Soviet balloon flights in the 1960's to altitudes near 30 km, seemed to indicate an even larger value, such as 2.016 cal cm⁻² min⁻¹ from Kondratiev et al. (1967). Soviet analyses of the probable value of the solar constant reflect this work; for example, 2.03 $\pm$ 0.15 cal cm⁻² min⁻¹ derived by Makarova and Kharitonov (1969).

More recently, Laue and Drummond (1968) have published a new value for the solar constant which includes direct measurements made from an X-15 aircraft at an altitude of about 82 km. They found it necessary to reduce the contribution for $\lambda > 6070 \text{ \AA}$ by about 7%, compared to Johnson's work, and derived a solar constant of 1.952 $\pm$ 0.02 cal cm⁻² min⁻¹ (1361 W m⁻²). The Mariner VI and VII spacecraft each carried a solar flux monitor to Mars in 1969. The data from these flights was quite consistent, giving a value of 1352.5 W m⁻² (Plamondon, 1969). Plamondon feels a probable error of $\pm 1\%$ was achieved.

An analysis of all solar constant measurements by the Standard's Subcommittee of the Solar Radiation Committee of the IES suggests that 1353 $\pm$ 21 W m⁻² be adopted as the best value for the solar constant (Thekaekara, 1970). However, there are still disagreements and uncertainties relative to the various measurements, and a JPL committee is continuing work on the problem. A very comprehensive and useful discussion of work to 1967, including extensive tables, has been prepared by Labs and Neckel (1968).

Using 1353 W m^{-2} for the solar constant, the total electromagnetic irradiation of Mars is

582.7 W m^{-2} at mean solar distance

709.0 W m^{-2} at perihelion

487.5 W m^{-2} at aphelion

Solar Spectral Irradiance

The distribution with wavelength of the Sun's power can be approximated roughly in visible light by that of a 5900°K blackbody, although the Sun's effective temperature (the temperature of a blackbody having the same total power output as the Sun) is only about 5765°K . The differences are caused by line blanketing, the effect of the absorption in the many Fraunhofer lines of the solar spectrum, and by the variation in photospheric depth (and therefore temperature) of the continuum observed at different wavelengths. The departure from blackbody radiation is far more extreme in the ultraviolet than in the visible wavelengths. Ultraviolet irradiance data is usually given in tabular form as a function of wavelength due to these variations. Table 1 presents the data cited by Thekaekara (1970) transformed to the mean solar distance of Mars.

Extreme ultraviolet, x-ray, and radio radiations from the Sun are direct functions of the solar cycle and of sporadic solar events. Such radiation constitutes an insignificant fraction ($< 2 \times 10^{-5}$) of the total power output of the Sun, but the very short wavelengths naturally have very high energies. Therefore, they play a major role in various excitation and ionization phenomena. Variations in these extreme wavelengths are discussed in the following subsections.

Extreme Ultraviolet Radiation

The "extreme ultraviolet" is that part of the electromagnetic spectrum beginning at approximately $50 \text{ \AA}$ and extending up to about $1800 \text{ \AA}$, at which point quartz begins to transmit and ordinary photographic emulsions become usable. Above $1800 \text{ \AA}$ there is strong and constant continuum radiation from the Sun. At wavelengths shorter than $1600 \text{ \AA}$ most solar power is in discrete emission lines. No absorption lines are found below about $1700 \text{ \AA}$. The entire extreme ultraviolet is dominated by the resonance line of atomic hydrogen (Lyman α), at $1215.7 \text{ \AA}$, which emits a greater flux than all other emission lines combined.

A basic problem in utilizing extreme ultraviolet solar data is the variation caused by the solar cycle, solar rotation, and solar flares. Although rocket-borne spectrometers, etc., have been used to study the Sun since shortly after World War II, reliable quantitative results are not easy to obtain even today, and it is difficult to separate true variations from calibration error, particularly when comparing results of different equipment and experimenters. In general, the variation for $\lambda > 1300 \text{ \AA}$ is probably small. Hinteregger (1970) suggests that the sum of various strong emission lines in the region $\lambda\lambda 280\text{-}1300$, probably shows a relative variation with solar cycle of about 75% that of the 10.7 cm radio emission, a factor of about two. The variation of lines and

Table 1. Solar spectral irradiance (from Thekaekara, 1970) transformed to Martian mean distance.

λ^a	P_λ^b	A_λ^c	D_λ^d	λ^a	P_λ^b	A_λ^c	D_λ^d
0.120	0.000004	0.00025843	0.00044	0.335	0.04657	1.93717	3.323
0.140	0.000001	0.00031447	0.00053	0.340	0.04627	2.16926	3.721
0.150	0.000003	0.00033600	0.00057	0.345	0.04605	2.40005	4.117
0.160	0.000010	0.00040062	0.00068	0.350	0.04708	2.63288	4.517
0.170	0.000027	0.00058586	0.00100	0.355	0.04665	2.86723	4.919
0.180	0.000054	0.00099079	0.00169	0.360	0.04601	3.09888	5.316
0.190	0.000117	0.00184373	0.00316	0.365	0.04876	3.35381	5.723
0.200	0.000461	0.007317	0.0081	0.370	0.05088	3.58491	6.150
0.210	0.000986	0.011969	0.0205				
0.220	0.00248	0.029286	0.0502	0.375	0.04984	3.83670	6.582
				0.380	0.04825	4.08192	7.003
0.225	0.00280	0.042468	0.0728	0.385	0.04730	4.32077	7.413
0.230	0.00287	0.0566407	0.0971	0.390	0.04730	4.55726	7.819
0.235	0.00255	0.0702102	0.1204	0.395	0.05122	4.80358	8.241
0.240	0.00271	0.0833813	0.1430	0.400	0.06156	5.08553	8.725
0.245	0.00311	0.0979525	0.1680	0.405	0.07082	5.41646	9.293
0.250	0.00303	0.113321	0.1944	0.410	0.07543	5.78210	9.920
0.255	0.00448	0.132103	0.226	0.415	0.07642	6.16170	10.571
0.260	0.00560	0.157303	0.269	0.420	0.07526	6.54092	11.222
0.265	0.00797	0.191227	0.328				
0.270	0.00999	0.236136	0.405	0.425	0.07293	6.91139	11.858
				0.430	0.07060	7.27023	12.473
0.275	0.00879	0.283091	0.485	0.435	0.07164	7.62584	13.083
0.280	0.00956	0.328969	0.564	0.440	0.07797	7.99984	13.725
0.285	0.0136	0.386801	0.663	0.445	0.08280	8.40176	14.415
0.290	0.0208	0.472630	0.810	0.450	0.08641	8.82479	15.140
0.295	0.0252	0.587433	1.007	0.455	0.08861	9.26237	15.891
0.300	0.0221	0.705682	1.210	0.460	0.08900	9.70638	16.653
0.305	0.0260	0.825978	1.417	0.465	0.08822	10.1494	17.413
0.310	0.0297	0.965120	1.655	0.470	0.08758	10.5803	18.167
0.315	0.0329	1.12160	1.924				
0.320	0.0358	1.29327	2.218	0.475	0.08805	11.0280	18.921
				0.480	0.08934	11.4715	19.681
0.325	0.04200	1.48766	2.552	0.485	0.08512	11.9077	20.430
0.330	0.04562	1.70671	2.928	0.490	0.08400	12.3305	21.155

^a λ : Wavelength in microns.
^b P_λ : Solar spectral irradiance averaged over small bandwidth centered at λ , in watts $\text{cm}^{-2} \mu^{-1}$.
^c A_λ : Area under the solar spectral irradiance curve in the wavelength range 0 to λ , mW cm^{-2} .
^d D_λ : Percentage of the solar irradiance associated with wavelengths shorter than λ .

Table 1. Solar spectral irradiance (from Thekaekara, 1970) transformed to Martian mean distance. (cont'd)

λ^a	P_λ^b	A_λ^c	D_λ^d	λ^a	P_λ^b	A_λ^c	D_λ^d
0.495	0.08443	12.7516	21.878	0.710	0.05790	27.9080	47.882
0.500	0.08366	13.1718	22.599	0.720	0.05660	28.4805	48.864
0.505	0.08270	13.5877	23.312	0.730	0.05557	29.0414	49.826
0.510	0.08107	13.9972	24.015				
0.515	0.07896	14.3973	24.701	0.740	0.05428	29.5907	50.769
0.520	0.07896	14.7921	25.379	0.750	0.05320	30.1281	51.691
				0.800	0.04769	32.6503	56.818
0.525	0.07978	15.1889	26.059	0.850	0.0426	34.9065	59.889
0.530	0.07935	15.5867	26.742	0.900	0.0383	36.9279	63.358
0.535	0.07832	15.9809	27.418	0.950	0.0360	38.7846	66.543
0.540	0.07681	16.3687	28.084	1.000	0.0321	40.4872	69.464
0.545	0.07556	16.7496	28.737	1.100	0.0255	43.3688	74.409
0.550	0.07431	17.1243	29.380	1.200	0.0208	45.6864	78.385
0.555	0.07409	17.4953	30.017	1.300	0.0171	47.5818	81.637
0.560	0.07302	17.8631	30.648				
0.565	0.07345	18.2293	31.276	1.400	0.0145	49.1585	84.342
0.570	0.07375	18.5972	31.907	1.500	0.0124	50.5003	86.645
				1.600	0.0105	51.6441	88.607
0.575	0.07405	18.9668	32.541	1.700	0.00870	52.6047	90.255
0.580	0.07388	19.3366	33.176	1.800	0.00685	53.3823	91.589
0.585	0.07375	19.7056	33.809	1.900	0.00543	53.9961	92.642
0.590	0.07323	20.0731	34.439	2.000	0.00444	54.4894	93.489
0.595	0.07246	20.4373	35.064	2.100	0.0039	54.9051	94.202
0.600	0.07177	20.7979	35.683	2.200	0.0034	55.2691	94.826
0.605	0.07095	21.1547	36.295	2.300	0.0029	55.5857	95.370
0.610	0.07043	21.5082	36.982				
0.620	0.06901	22.2054	38.098	2.400	0.0028	55.8700	95.858
0.630	0.06763	22.8886	39.270	2.500	0.0023	56.1242	96.294
				2.600	0.0021	56.3439	96.671
0.640	0.06651	23.5593	40.421	2.700	0.0019	56.5399	97.007
0.650	0.06509	24.2173	41.550	2.800	0.00168	56.7165	97.3103
0.660	0.06401	24.8629	42.657	2.900	0.00151	56.8759	97.5838
0.670	0.06272	25.4965	43.744	3.000	0.00134	57.0180	97.8277
0.680	0.06147	26.1175	44.810	3.100	0.00112	57.1408	98.0383
0.690	0.06040	26.7268	45.855	3.200	0.000974	57.2455	98.2179
0.700	0.05897	27.3269	46.879	3.300	0.000827	57.3355	98.3724
^a λ = Wavelength in microns. ^b P_λ = Solar spectral irradiance averaged over small bandwidth centered at λ , in watts $\text{cm}^{-2} \mu^{-1}$. ^c A_λ = Area under the solar spectral irradiance curve in the wavelength range 0 to λ , mW cm^{-2} . ^d D_λ = Percentage of the solar irradiance associated with wavelengths shorter than λ .							

Table 1. Solar spectral irradiance (from Thekaekara, 1970) transformed to Martian mean distance. (cont'd)

λ^a	P_λ^b	A_λ^c	D_λ^d	λ^a	P_λ^b	A_λ^c	D_λ^d
3.400	0.000715	57.4126	98.5047	9.0	0.0000164	58.234370	99.913939
3.500	0.000629	57.4798	98.6200	10.0	0.0000108	58.247939	99.937220
3.600	0.000582	57.5406	98.7238	11.0	0.00000732	58.256986	99.952742
3.700	0.000530	57.5961	98.8192	12.0	0.00000517	58.263232	99.963458
3.800	0.000478	57.6465	98.9056	13.0	0.0000037	58.267691	99.971108
3.900	0.000444	57.6926	98.9847	14.0	0.0000024	58.270749	99.976356
4.000	0.00041	57.7353	99.0579	15.0	0.0000021	58.272980	99.980190
4.100	0.00037	57.7745	99.1252	16.0	0.0000016	58.274863	99.983414
4.200	0.00034	57.8098	99.1861	17.0	0.0000013	58.275918	99.985964
4.300	0.00031	57.8421	99.2412	18.0	0.0000010	58.277534	99.987997
4.400	0.00028	57.8714	99.2915	19.0	0.00000086	58.278482	99.989623
4.500	0.00025	57.8981	99.3373	20.0	0.00000067	58.279257	99.990953
4.600	0.00023	57.9222	99.3787	25.0	0.000000263	58.281639	99.995836
4.700	0.00021	57.9438	99.4160	30.0	0.000000129	58.282617	99.996718
4.800	0.00019	57.9640	99.4504	35.0	0.0000000689	58.283112	99.997568
4.900	0.00018	57.9826	99.482195	40.0	0.000000040	58.283388	99.998037
5.000	0.0001650	57.999810	99.511500	50.0	0.000000016	58.283672	99.998525
6.000	0.00007539	58.119998	99.717708	60.0	0.0000000082	58.283793	99.998736
7.000	0.0000426	58.179014	99.818965	80.0	0.000000003	58.283905	99.998928
8.000	0.0000258	58.213261	99.877723	100.0	0.000000001	58.283948	99.999002
				1000.0	0	58.284534	100.0
^a λ Wavelength in microns. ^b P_λ Solar spectral irradiance averaged over small bandwidth centered at λ , in watts $\text{cm}^{-2} \mu^{-1}$. ^c A_λ Area under the solar spectral irradiance curve in the wavelength range 0 to λ , mW cm^{-2} . ^d D_λ Percentage of the solar irradiance associated with wavelengths shorter than λ .							

radio emission with solar rotation is more or less comparable, again a factor of about two (Hinteregger, 1970). In both cases, individual emission lines show changes ranging from very small to several times the average. Variation of individual lines in the $\lambda\lambda$ 30-280 region is uncertain, but at the high energy end of this region Kreplin (1970) found a factor-of-20 increase from sunspot minimum to sunspot maximum in a band from 44 Å to 60 Å.

The data on spectral irradiance in Table 2, Part 1, were obtained from the satellite OSO-III on March 11, 1967, a time of medium solar activity (Hinteregger, 1970), and have been transformed to Martian mean distance, as have Parts 2 and 3 of Table 2. The 10.7 cm radio flux at Earth on that date

was $144 \times 10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1}$. The data in Table 2, Part 2, were obtained by rocket at an altitude of 210 km on April 4, 1969, and were quoted by Hinteregger (1970) from unpublished data of Heroux et al. The 10.7 cm flux at Earth was $177 \times 10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1}$, indicating somewhat greater solar activity but still not "high" activity. The data in Table 2, Part 3, are from unpublished work by Manson, quoted by Hinteregger (1970). They were taken on August 8, 1967, when the 10.7 cm flux level at Earth was $143 \times 10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1}$, a medium active Sun. These data collectively offer a reasonable picture of the average extreme ultraviolet flux. A first approximation to the flux level under other conditions can be obtained by multiplying the UV flux by the ratio of the 10.7 cm radio flux level on Earth at the time in question to $150 \times 10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1}$. Unless the radio flux ratio varies more than 30% from unity, there is little point in making the correction however, since there is at least that much uncertainty in the data.

X-rays

Although a more precise definition could be given in terms of the origin of the photon, the region of the electromagnetic spectrum between 0.1 Å and about 50 Å is normally considered the x-ray region. The x-radiation from the Sun consists of a continuum, which probably originates in recombination and bremsstrahlung radiation of plasmas in active solar coronal regions, and superimposed emission lines of very highly ionized coronal atoms, many of them stripped down to one electron.

There are large variations in solar x-ray flux, even during nonflare conditions, and the variation increases toward shorter wavelengths. The flux at 1 AU in the 44 Å-60 Å band was $3 \times 10^{-4} \text{ W m}^{-2}$ in 1969, while at sunspot minimum in 1964 it was only $1.5 \times 10^{-5} \text{ W m}^{-2}$ (Kreplin, 1970). In the 8 Å-20 Å band, the flux was $\sim 3 \times 10^{-5} \text{ W m}^{-2}$ in 1969 and more than 200 times less in 1964, undetectable in the equipment then available (Kreplin, 1970). The 1969 flux at 1 AU in the 0 Å-8 Å band was $\sim 2 \times 10^{-6} \text{ W m}^{-2}$. As for visible radiation, these flux figures can be transformed to Martian equivalents through multiplication by the inverse square of the distance in astronomical units, a factor of 0.4307 for the mean distance of Mars from the Sun.

There is a sizable variation, of shorter period, as the Sun rotates and brings regions of greater and lesser activity into view. During a 7-month period of observations, from October 1967 through April 1968, using the satellite QSO-4, there was a 7-to-1 variation in 8 Å-16 Å flux, a 12-to-1 variation in 3 Å-9 Å flux, and a 120-to-1 variation in 1 Å-3 Å flux (Pounds, 1970). In the 44 Å-60 Å band, the variation was only about 1.7 to 1 during March 1966 (Kreplin, 1970).

There appears to be a close relationship between solar H α flares and x-ray bursts or flares. Pounds (1970) suggests it is quite probable that the correlation is 100%. During an importance 2B flare on April 11, 1967, Pounds (1970) quotes data showing the 8 Å-12 Å band flux increased by a factor of 20 in five minutes, and then decayed much more slowly (perhaps over several hours). Whereas x-rays may be detectable only down to 1.5 Å or 2 Å during a quiet Sun, x-rays with energies above 22 keV (≤ 0.6 Å) are common during flares (Pounds, 1970).

Table 2. Solar XUV spectral irradiance (from Hinteregger, 1970)
transformed to Martian mean distance.

Part 1							
λ or Range (Å)	Identification	I_o^a	ϕ_o^b	λ or Range (Å)	Identification	I_o^a	ϕ_o^b
1306.0-1304.9	O I	0.00646	0.43	835 group	O II, III	0.00530	0.22
1302.2	O I	0.0035	0.23	830-800	H cont.	0.00818	0.34
1265.0	Si II	0.0031	0.20	911-800	unresolved	0.00099	0.043
1260.7	Si II	0.0016	0.099	911-800	integral	0.086	3.6
1242.8	N V	0.0020	0.12	800-770	H cont.	0.0042	0.17
1238.8	N V	0.0030	0.19	790.2, 790.1	O IV	0.0028	0.11
1215.7	H Ly- α	~2.2	~129	787.7	O IV	0.0014	0.056
1206.5	Si III	0.025	1.6	786.5	S V	0.00086	0.034
1175 group	C III	0.016	0.95	780.3	Ne VIII	0.0013	0.052
1128.3	Si IV	0.0020	0.12	770.4	Ne VIII	0.0025	0.099
1122.5	Si IV	0.0016	0.095	770-740	H cont.	0.0022	0.082
1085 group	N II	0.00465	0.25	765.1	N IV	0.0020	0.078
1037.6	O VI, C II	0.014	0.73	760	O V	0.00082	0.034
1031.9	O VI	0.019	0.99	740-710	H cont.	0.0010	0.039
1310-1027	unresolved	0.029	1.6	710-680	H cont.	0.00052	0.017
1310-1027	excl. H Ly- α	0.13	7.54	703 group	O III	0.0028	0.099
1310-1027	integral	~2.3	~138	800-630	unresolved	0.00482	0.17
1025.7	H Ly- β	0.029	1.5	800-630	integral	0.028	1.03
990 group	N III	0.00521	0.26	629.7	O V	0.012	0.40
977.0	C III	0.039	1.9	625.3	Mg X	0.0035	0.11
972.5	H Ly- γ	0.00706	0.34	609.8	Mg X	0.0069	0.22
949.7	H Ly- δ	0.0031	0.17	599.6	O III	0.0012	0.034
944.5	S VI	0.00082	0.043	584.3	He I	0.013	0.38
937.8	H Ly- ϵ	0.0020	0.095	554 group	O IV	0.00474	0.13
933.4	S VI	0.0012	0.056	521.0	Si XII	0.0032	0.082
930.7	H Ly- ζ	0.0012	0.056	508 group	O III	0.0013	0.034
926.2	H Ly- η	0.0012	0.056	504 -	He I cont.	0.0086	0.22
1027-911	unresolved	0.011	0.521	499.3	Si XII	0.00655	0.16
1027-911	integral	0.099	5.00	465.2	Ne VII	0.0029	0.069
911-890	H cont.	0.030	1.4	630-460	unresolved	0.00719	0.19
904 group	C II	0.0012	0.056	630-460	integral	0.073	2.0
890-860	H cont.	0.027	1.2	460-370	integral	0.013	0.27
860-830	H cont.	0.015	0.65	368.1	Mg IX	0.013	0.24
^a I_o flux, $\text{erg cm}^{-2} \text{sec}^{-1}$. ^b I_o flux, in units of $10^9 \text{ photons cm}^{-2} \text{sec}^{-1}$.							

Table 2. Solar XUV spectral irradiance (from Hinteregger, 1970)
transformed to Martian mean distance. (cont'd)

Part 1 (cont'd)							
λ or Range ($\text{\AA}$)	Identification	I_o^a	ϕ_o^b	λ or Range ($\text{\AA}$)	Identification	I_o^a	ϕ_o^b
364.8	Fe XVI	0.0039	0.073	284.1	Fe XV	0.033	0.47
360.7		0.0086	0.16	370-280	unresolved	0.0526	0.874
335.4		0.019	0.31	370-280	integral	0.28	4.44
303.8	He II	0.152	2.3				
Part 2							
λ or Range ($\text{\AA}$)	Identification	I^c	λ or Range ($\text{\AA}$)	Identification	I^c		
280-231	integral	0.099	176-153	integral	0.047		
231-205	integral	0.056	205-153	integral	0.211		
280-205	integral	0.155	153-100	integral	0.026		
205-176	integral	0.164					
Part 3							
λ or Range ($\text{\AA}$)	Identification	I^c	λ or Range ($\text{\AA}$)	Identification	I^c		
128-120	integral	0.0009	80-70	integral	0.011		
120-110	integral	0.0017	66.3	Fe XVI	0.0009		
103.6, 105.2	Fe IX	0.00082	70-60	integral	0.014		
110-100	integral	0.0051	50.5, 50.7, 55.3	Si X/IX	0.0039		
94.0, 96.1	Fe X	0.0013	60-50	integral	0.013		
100-90	integral	0.0090	44.1	Si XII	0.0013		
80.5, 86.8	Fe XII/XI	0.0009	50-40	integral	0.0090		
90-80	integral	0.013	80-40	integral	0.0465		
120-80	integral	0.028	33.6	C VI	0.0009		
76.0	Fe XIII	0.0009					

^a I_o flux, $\text{erg cm}^{-2} \text{sec}^{-1}$.

^b I_o flux, in units of $10^9 \text{ photons cm}^{-2} \text{sec}^{-1}$.

^c I_o flux, $\text{erg cm}^{-2} \text{sec}^{-1}$.

Radio Wave Radiation

At millimeter wavelengths, the Sun radiates very like a blackbody at a temperature of about 5800°K . Near one centimeter, the brightness temperature begins to increase rapidly, however, and by the time a wavelength of three meters is reached, the brightness temperature (of even the quiet Sun) has risen to 10^6°K (Smith, 1967). The disturbed Sun may exhibit a brightness temperature of 10^{10}°K at wavelengths of 3-10 meters (Castelli et al., 1965), but the flux involved is only about $10^{-18} \text{ W m}^{-2} \text{ Hz}^{-1}$, at 1 AU. The detailed radio frequency behavior of the Sun is quite complex, and is of interest primarily in attempting to understand the Sun itself, as the small amounts of power and low energies involved have little effect upon the Moon or planets.

It is useful to note that there is excellent correlation between the 10.7 cm flux and the sunspot area on the solar disk. The correlation with XUV flux was noted in previous paragraphs, and good correlation exists with the x-ray flux (Pounds, 1970). Daily measurements of the 10.7 cm solar flux have been made since the beginning of 1947, to serve as an indication of the level of solar activity (Castelli et al., 1965).

Absorption in the Martian Atmosphere

The atmosphere of Mars is principally CO_2 , which has no significant absorptions in the visible part of the spectrum. Rayleigh scattering will remove perhaps 3% of the incoming radiation at $6000 \text{ \AA}$ (Young, 1969). There appear to be atmospheric aerosols generally present, but these are quite tenuous (Leovy et al., 1971) and in all probability create little atmospheric opacity or loss of contrast in the visible spectrum (Smith, Young, and Leovy, 1970; Van Blerkom, 1971). There is also evidence of occasional major dust storms which do cause great opacity (see Section 4.1). Most of the time the solar spectral irradiance falling on the Martian surface, at visible wavelengths, must be virtually that which is incident upon the upper atmosphere.

In the infrared, CO_2 has very strong rotation-vibration bands absorbing at 15, 4.3, and 2.7μ , plus additional weaker absorptions extending down to the visible, but growing weaker with decreasing wavelength. The rare dust storm would also create infrared opacity at wavelengths roughly equal to the particle size or smaller.

In the ultraviolet, Barth and Hord (1971) have presented evidence for scattering about three times as great as would be expected from pure Rayleigh scattering. This is not necessarily inconsistent with the observations in the visible, but does raise some question of disagreement unless rather special assumptions are made about particle size or distribution. Ozone is the principal atmospheric absorber between $2000 \text{ \AA}$ and $3000 \text{ \AA}$, and there is evidence for perhaps $10 \mu\text{-atm}$ of O_3 in the Martian atmosphere (see Section 5.1). Nevertheless, most sunlight $\lambda > 1800 \text{ \AA}$ must still reach the Martian surface. While there are significant absorptions by CO_2 below $1800 \text{ \AA}$, there is relatively little solar continuum to be absorbed at short wavelengths. Observational studies of Martian aeronomy have been initiated by Barth et al. (1971) with their Mariner 6 and 7 experiment, but quantitative details of ultraviolet fluxes reaching the

ground at $\lambda < 1800 \text{ \AA}$ are not yet available. It can be stated that most x-rays should be blocked from the Martian surface by the atmosphere, while perhaps half of the γ -rays reach the surface (see the following subsection, especially Fig. 2).

6.1 THE PARTICLE ENVIRONMENT

Particles arrive in the vicinity of Mars from a variety of sources. By far the largest flux comes from the Sun, gently in the form of solar wind, or explosively from solar flares and flare-related phenomena. By comparison, the flux of cosmic rays is negligible, but the effects of these particles are significant since one cosmic ray particle may contribute as much as 10 joules of energy to the Martian atmosphere and surface, and create thousands of radioactive nuclei. The nature and effects of the solar wind, solar flares, and cosmic rays are discussed in this subsection.

The Solar Wind

The solar wind originates in the solar chromosphere, a sheath about 0.01 R thick, located outside the optically observed solar surface or photosphere. The temperature of the chromosphere rises from $5 \times 10^3 \text{ K}$, at its boundary with the photosphere, to about 10^6 K at its outer limit, where it merges into the corona and then continues to rise to a maximum of about $2 \times 10^6 \text{ K}$ in the corona. This nonequilibrium increase in temperature is believed due to acoustical or magnetic noise created inside the photosphere, from turbulent hydrogen convection, and absorbed preferentially by the thinning gases of the chromosphere (Brandt, 1970, Chap. 3). The acceleration of the hot chromospheric gases into a supersonic plasma flow has been studied by Parker (1958). His theoretical treatment uses the confining force of the Sun's gravity to form a "converging throat" analogous to the throat of a rocket engine. Hydrodynamic acceleration to sonic speeds in the throat leads to continued supersonic acceleration and direct motion in the rarefied gas beyond the throat. Only the Parker model has satisfactorily accounted for the high velocities and temperatures observed in the solar wind.

Parameters generally describing the composition and state of the solar wind are given in Tables 3 through 5. These are the results of spacecraft experiments carried out in the area roughly between the orbits of Earth and Venus and then extrapolated to Mars' distance from the Sun (although Mariner IV carried an ion chamber which functioned part of the way to Mars and a solar plasma experiment which operated throughout the mission).

The composition of the solar wind is known only in barest outline. The earliest experiments on Mariner II (see Neugebauer and Snyder, 1962) revealed alpha particles in the spectrum, along with protons. The ratio of alphas to protons varies widely, from 0 to about 0.25, averaging about 0.05 (Strong et al., 1970). The photospheric value is 0.1. The (average) preference for ejection of protons over alpha particles is understood in terms of diffusion in the corona after the plasma has been thoroughly mixed in the chromosphere (Jokipii, 1966).

Table 3. Solar wind proton (H^+) data for Earth and derived estimates for Mars (Neugebauer, 1971).

Solar wind proton data for	v Velocity, km sec ⁻¹	n Density, cm ⁻³	T Temperature, °K	nv* Directional flux	nmv ² /2* Energy density, ergs cm ⁻³	mv ² /2 Energy per particle, ev
Earth						
Minimum	150	1	6×10^3	1×10^7	3×10^{-10}	1×10^2
Average	400	6	1×10^5	3×10^8	1×10^{-8}	8×10^2
Maximum	1000	200	1×10^6	5×10^9	2×10^{-7}	5×10^3
Mars						
Minimum at aphelion	150	0.2	6×10^3	4×10^6	1×10^{-10}	1×10^2
Average at aphelion	400	2	1×10^5	1×10^8	5×10^{-9}	8×10^2
Average at perihelion	400	3	1×10^5	2×10^8	7×10^{-9}	8×10^2
Maximum at perihelion	1000	100	1×10^6	3×10^9	1×10^{-7}	5×10^3
*Extreme values of nv and nmv ² /2 do not correspond to the product of extreme values of n and v, due to a generally inverse relation between n and v.						

Table 4. Solar wind alpha-particle (He^{++}) data for Earth and derived estimates for Mars (Neugebauer, 1971).

Solar wind alpha-particle data for	v Velocity, km sec ⁻¹	n Density, cm ⁻³	T Temperature, °K	nv* Directional flux	nmv ² /2* Energy density, ergs cm ⁻³	mv ² /2 Energy per particle, ev
Earth						
Minimum	150	0	6×10^3	0	0	5×10^2
Average	400	0.3	4×10^5	1×10^7	1×10^{-9}	3×10^3
Maximum	1000	2	2×10^6	1×10^8	1×10^{-8}	2×10^4
Mars						
Minimum at aphelion	150	0	6×10^3	0	0	5×10^2
Average at aphelion	400	0.1	4×10^5	4×10^6	4×10^{-10}	3×10^3
Average at perihelion	400	0.1	4×10^5	5×10^6	5×10^{-10}	3×10^3
Maximum at perihelion	1000	1	2×10^6	5×10^7	5×10^{-9}	2×10^4
* Extreme values of nv and nmv ² /2 do not correspond to the product of extreme values of n and v, due to a generally inverse relation between n and v.						

Table 5. Solar wind electron data for Earth and derived estimates for Mars (Neugebauer, 1971).

Solar wind electron data for	v Velocity, km sec ⁻¹	n Density, cm ⁻³	T Temperature, °K	$\bar{nv}_{th}/4$ Omnidirectional flux, ^b cm ⁻² sec ⁻¹	$3/2 nkT$ Energy density, ergs cm ⁻³	$2T$ Energy per particle, eV
Earth						
Minimum	150	1	7×10^4	4×10^7	2×10^{-11}	c
Average	400	6	1.5×10^5	3×10^8	2×10^{-10}	1×10^1
Maximum	1000	200	2×10^6	1×10^{10}	6×10^{-9}	2×10^2
Mars						
Minimum at aphelion	150	0.2	7×10^4	1×10^7	7×10^{-12}	c
Average at aphelion	400	2	1.5×10^5	1×10^8	7×10^{-11}	1×10^1
Average at perihelion	400	3	1.5×10^5	2×10^8	1×10^{-10}	1×10^1
Maximum at perihelion	1000	100	2×10^6	5×10^9	3×10^{-9}	2×10^2

^aDirected away from Sun.
^b $v_{th} = \sqrt{2kT/m}$.

The electrostatic analyzer aboard Vela III established the presence of $^3\text{He}^{++}$, several charge states of ^{16}O and possibly ^{12}C (Bame et al., 1968). The $^3\text{He}/^4\text{He}$ ratio varied from 1.3×10^{-3} to less than 2×10^{-4} , and the He/O ratio from 25 to 80. The two spectra yielding these results were made possible by short periods of very low temperatures ($<10^4\text{K}$), which permitted peaks to be resolved.

The density of protons is derived from flux and bulk velocity measurements made aboard spacecraft. Velocities are derived from energy-per-unit-charge measurements, made with electrostatic analyzers (either Faraday cups or hemispherical spectrometers). High bulk velocities are correlated with low densities, implying a relatively constant flux. The average electron density has been measured directly by means of radio propagation experiments (e.g., Koehler, 1967). These measurements employ the differences in the phase lag of two, different frequency, rf signals beamed to a distant spacecraft. There have also been direct measurements of electron fluxes and velocity distributions by electrostatic analyzer. The particle densities are consistent with bulk electrical neutrality (no excess of electrons or protons plus ions).

The characteristics of the solar wind are subject to wide variations as the ranges of different quantities has shown. The highest velocities and greatest temperatures are attained during solar maximum, which is the period of peak activity during the Sun's 11-year cycle of activity. More sunspots appear during this period, beginning early in the cycle in smaller numbers at high solar latitudes and increasing in number and progressing toward the equator as the cycle

advances. Sector structure of the solar wind's magnetic field (see Magnetic Fields) becomes more complicated during peak solar activity, and solar flares and geomagnetic storms occur frequently.

Insofar as Mars has no magnetic field (see Magnetic Fields), the solar wind is deflected by the ionosphere and a bow wave is formed, not dissimilar to that formed by interaction with the Earth's magnetic field, but much closer to the planet (see Fig. 1). Observations of the Martian bow wave are nonexistent, but a theoretical study by Spreiter, Summers, and Rizzi (1970), indicates that it should be less than half a planetary radius above the surface normal to the flow.

The details of the interaction of the solar wind and the Martian ionosphere have not been studied, but Cloutier, McElroy, and Michel (1969) indicate the possibility that the solar wind may provide a source of hydrogen for Mars.

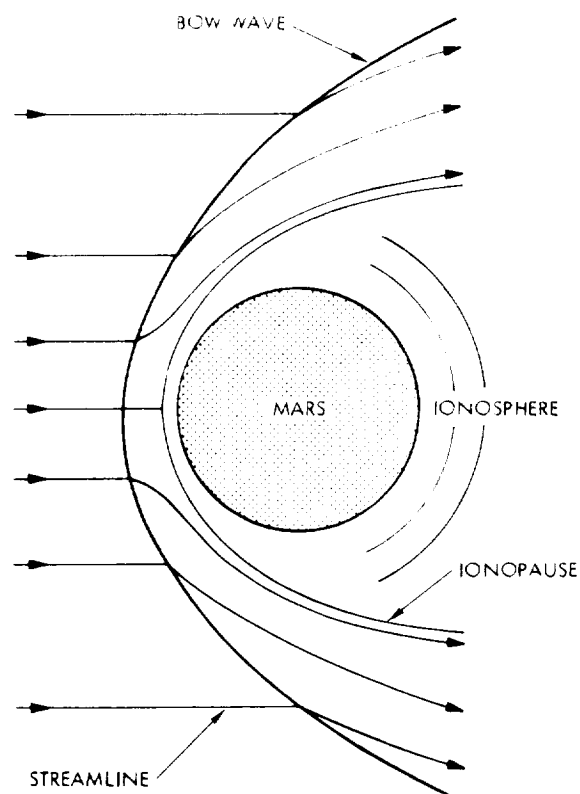


Fig. 1. Principal features of solar wind flow past Mars (after Spreiter, Summers, and Rizzi, 1970).

Solar Cosmic Rays

Solar cosmic rays are solar particles which are distinguished from the particles of the solar wind by their much greater energy, typically 100 Mev/nucleon to over 1000 Mev/nucleon as opposed to a maximum of 0.02 Mev for an α particle and even less for protons and electrons in the solar wind. They are generated by various sorts of disturbances in the solar photosphere, chromosphere, and corona (McDonald, 1970). The most energetic and abundant particles are associated with solar flare events when the particles are expelled by what appears to be an explosion in the chromosphere. After one solar rotation (27 days) the remnants of the flare again release particles, with reduced energies, in the direction of the Earth. These are termed "recurrent flare" particles. Even during relatively quiet periods, active centers in the chromosphere release broad beams of energetic particles. These particles sometimes pass 1 AU in a relatively undisturbed state and are called "active center related"; alternatively they arrive in the turbulent plasma behind an interplanetary shock, in which case they are called "energetic storm particles." Between the active centers, the solar cosmic rays diminish in relative intensity, but a small number of energetic particles are always present at 1 AU. It is not known whether these represent some form of high energy emission from the quiet Sun, or the time-averaged echo of many solar events trapped in the microstructure of the interplanetary medium.

The most energetic flare-associated-particles arrive at 1 AU several hours after the visual observation of a solar eruption, perhaps 10 to 15 times later than would be expected for straight-line trajectories. The rise in flux is rapid and may peak only a few hours after the onset and then slowly diminish in a few days to the quiet Sun value. Peak fluxes vary from 10^3 to 10^5 times the quiet Sun flux. Energy spectra are described by a power law:

$$\frac{dJ}{dE} = KE^{-\gamma} \quad (1)$$

where J is the flux of particles ($\text{cm}^{-2} \text{ sec}^{-1} \text{ sterad}^{-1}$), E is the energy-per-unit-mass (MeV nucleon^{-1}) and K and γ are parameters which may vary with flare intensity or with time within a given flare. The exponent γ ranges from 2.5 to 3.5 and tends toward the smaller value for the intense periods of flares. (Smaller values of γ make the spectrum flatter, giving more weight to higher energy particles). Instantaneous fluxes reach as high as $10^3 \text{ cm}^{-2} \text{ sec}^{-1} \text{ sterad}^{-1}$, but the time-averaged flux (averaged over the solar cycle) is very much lower, probably on the order of $80 \text{ protons cm}^{-2} \text{ sec}^{-1} (4 \text{ sterad})^{-1}$ (Shedlovsky, et al., 1970).

The recurrent events represent only a small portion of the initial events. Flux maxima are nearly symmetrical in tune, rising to approximately 2 to 10 times the quiet background, and lasting only a few hours. They contribute little to the sustained flux at 1 AU.

The particles associated with active centers display broad symmetrical flux increases, which may rise a few hundred times above the quiet flux, and last several days. These positively charged particle fluxes are distinguished from other fluxes by their anticorrelation with energetic electron fluxes.

The energetic storm particles appear in the wake of a plasma shock wave propagating out from a solar flare. They are believed to be trapped in the turbulent magnetic flux behind the shock. Their fluxes may reach 100 times the quiet flux level and diminish in a few days.

Solar cosmic rays are believed to represent essentially the solar composition. The ratio H/He derived from induced radioactivities in lunar materials is 8:1, substantially in agreement with the photospheric value of 10:1.

The Martian surface dosages for solar flare protons are given in Table 6, taken from calculations of Foelsche and Wilson (1970). These particles constitute a significant natural radiation source on the Martian surface.

"Galactic" Cosmic Rays

"Galactic" cosmic rays are extremely energetic nuclear particles, of all atomic numbers, and energetic electrons and gamma rays. Most of the rays are nuclear, and most of the nuclear particles are protons. Origins of the rays are unknown, and speculation about their source is quite varied. One theory suggests that stochastic collisions between particles and fast moving turbulent gas clouds will, on the average, accelerate the particles. Another theory

Table 6. Maximum number of solar event protons (cosmic rays) reaching the Martian surface, assuming an atmosphere consisting of 6 mb of CO₂ (Foelsche and Wilson, 1970).

Solar event protons (Cosmic rays)	Single event	Yearly		
Proton energy, Mev	Fluence (>E), protons/cm ²	Maximum Fluence (>E), protons/cm ²	Near Sunspot minimum (1973-1976) Fluence (>E), protons/cm ²	
			Maximum	Most probable
>10	2.2×10^7	6.4×10^7	2.4×10^7	$<1.5 \times 10^6$
>20	2.1×10^7	5.9×10^7	2.2×10^7	$<1.4 \times 10^6$
>100	1.6×10^7	4.0×10^7	1.7×10^7	$<1.1 \times 10^6$
>200	1.1×10^7	1.8×10^7	1.2×10^7	$<7.7 \times 10^5$
>300	7.2×10^6	9.6×10^6	7.7×10^6	$<5.0 \times 10^5$

suggests that powerful supernova are frequent enough in our galaxy to supply all the cosmic rays. Other theories include synchrotron acceleration in growing dipole magnetic fields, and the spiral acceleration of particles released by pulsars in the pulsar's co-rotating magnetic field. It is almost certain that the rays are formed and accelerated by a hierarchy of means, because they span energies which exceed the means of any one mechanism. Disturbances on normal stars (see the preceding paragraphs on solar cosmic rays) may provide the abundant, lowest energy particles. A variety of galactic disturbances may give rise to, and accelerate, the intermediate energy particles. But intergalactic means are required to accelerate the high energy particles, whose magnetic rigidities are too large to be contained by galactic magnetic fields. (For reviews of cosmic ray physics, see Rossi, 1964, and especially Hayakawa, 1969.)

The flux of energetic galactic cosmic rays is very nearly constant and isotropic, although there is some modulation by solar activity. The flux of nuclear particles with energies greater than 100 MeV/nucleon is about $2 \text{ cm}^{-2} \text{ sec}^{-1}$ at 1 AU. The Mariner IV cosmic ray telescope indicated a 5% increase in the integral proton flux and a 30% increase in α -particle flux at 1.5 AU (O'Gallagher and Simpson, 1967). The electron flux is about 10% of the heavier particle flux. The lowest energy portion receives episodic contributions from solar flares whose most energetic components may reach several GeV/nucleon. These are also distinctly anisotropic (see the preceding section). Other disturbances to the continuity of the flux occur as a result of the 11-year solar activity cycle. Early experiments revealed a flux variation at sea level of about 6%; higher flux at solar minimum and lower flux at solar maximum. These early results were misleading about the total effect of solar maximum, because only the most energetic particles were observed at sea level. Above the Earth's atmosphere, the low energy cosmic ray flux is heavily attenuated during the solar maximum, while the high energy flux is much less affected. Decreases in cosmic ray fluxes are also observed in conjunction with magnetic storms. Magnetic storms are believed to be shock waves from chromospheric explosions propagating through the plasma medium. These decreases, called Forbush decreases, affect cosmic particles in a much broader band, than do those related to solar maxima. These phenomena are thought to reflect the increased opacity of a turbulent magnetic field. The magnetic fields, related to the micro- and meso-structure of the solar plasma, could be carried several AU into interplanetary space, which would provide a diffuse scattering shield against the low energy galactic particles. Those particles with higher magnetic rigidity are less affected. The shock waves apparently carry stronger and more turbulent fields, thereby providing a more effective shield against those particles with higher magnetic rigidity.

The differential energy spectrum at solar minimum rises between 100 MeV/nucleon and 1 GeV/nucleon, reaches a maximum between 1 and 2 GeV/nucleon, and then falls monotonically to the highest energies observed. At solar maximum it is this low energy part of the spectrum which is depressed, pushing the maximum in the spectrum out to higher energies, ~2-4 GeV/nucleon. The energy spectrum below 1 GeV/nucleon may be modeled by

$$\frac{dJ}{dE} \sim E^{1.4} (0.5 + E)^{-4}; \quad E \leq 1 \text{ GeV/nucleon} \quad (2)$$

where j is the flux [$\text{cm}^{-2} \text{sec}^{-1} (4\pi \text{sterad})^{-1}$] and E is expressed in GeV/nucleon (Hayakawa, 1969). Between 1 and 5 GeV the spectrum is better expressed by

$$\frac{dJ}{dE} \sim (0.6 + E)^{-2.5}; \quad \frac{1 \text{ GeV}}{\text{nucleon}} \leq E \leq \frac{5 \text{ GeV}}{\text{nucleon}} \quad (3)$$

This becomes indistinguishable from the $E^{-2.5}$ law above 5 GeV/nucleon, which holds accurately to about 10^7 GeV. At 10^7 GeV the spectrum steepens somewhat. Particles with energies greater than 10^7 GeV have relatively short diffusion lifetimes in the fluctuating magnetic fields of the galaxy. It is speculated that the steepening of the spectrum at 10^7 GeV represents the loss of more energetic galactic particles, or the less favorable capture of intergalactic particles. After 10^9 GeV the spectrum again recovers its $E^{-2.5}$ shape out to the highest energy observed, $\sim 10^{11}$ GeV ($\sim 10^{20}$ eV, or ~ 10 joules, a truly macroscopic energy!).

Composition of the cosmic ray flux does not correspond to the solar abundance, or to that assumed to be the "cosmic" abundance. (For example, see Cameron, 1968.) Abundance investigators divide the elements into several broad categories: light (L), $Z = 3-5$; medium (M), $Z = 6-9$; three categories of heavy (H_3), $Z = 10-15$; (H_2), $Z = 16-19$; (H_1), $Z = 20-23$. Very heavy (VH) refers to the iron group, $Z = 24-28$, and very, very heavy (VVH) to everything with $Z \geq 29$. The α/p ratio, $1/8$, is about the same in cosmic rays as in the solar and other cosmic abundances, while the cosmic rays are much richer in L nuclei, Li, Be, and B. The M nuclei, C, N, O, and F, are qualitatively the same. The dominance of even- Z over odd- Z elements is already evident here. The H, VH, and VVH elements are more abundant in cosmic rays, by almost two orders of magnitude in the case of the VH elements. The H_2 group, S, Cl, Ar, and K, is enriched relative to the other H elements. This subgroup forms a minimum in the solar and cosmic abundance curves which is filled in for cosmic rays. The abundances for these groups, relative to the cosmic ray proton abundance, are: L, $\sim 1 \times 10^{-3}$; M, 3×10^{-3} ; H, 1×10^{-3} ; and VH, 3×10^{-4} .

Most of the energy of cosmic rays which impinges upon planetary matter, such as Mars' atmosphere and surface, is given up in nuclear cascade reactions. The flux of primary particles decreases with depth as nuclei are lost through internuclear collisions and as lower energy particles come to a stop. But the overall flux of particles rises to a maximum as secondary particles, protons, neutrons, and mesons are produced by collisions. The atmosphere of a planet thus absorbs the incident particles, but can multiply the net particle flux.

Figure 2 shows charged-particle flux at the planet surface versus atmospheric mass. The thin atmosphere on Mars increases the flux of charged particles expected at the surface, in comparison with that in space. With a 7-mb surface pressure on Mars, the flux at the surface increases by 90%. Haines (1967) concludes that the fast neutron flux arising from cosmic ray collisions with atmospheric atoms does not exceed $50 \text{ cm}^{-2} \text{sec}^{-1}$. This flux is probably insufficient to produce a measurable radiation field by neutron activation of the surface (causing emission of electrons and γ -rays in resultant beta-decay processes) but low level radioactivity and stable isotope shifts may be detectable. The flux drops off with depth to a few percent of its initial value after traversing two meters of typical surface material.

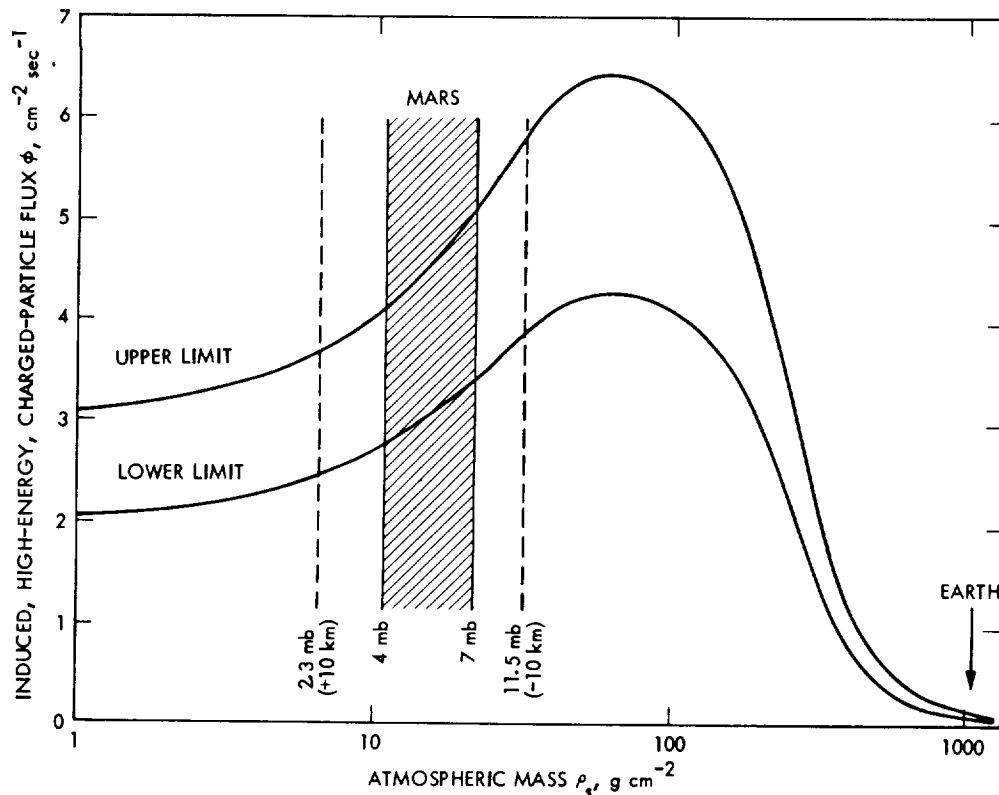


Fig. 2. Cosmic-ray-induced charged-particle flux at the surface versus atmospheric mass for Mars and Earth. The dotted lines indicate values for elevations 10 km above and below a mean elevation at 5.3 mb. Based upon Haines, 1967.

6.2 MAGNETIC FIELDS

Solar Interplanetary Magnetic Field

The solar wind, being a nearly perfect conductor, carries with it the magnetic field lines which were trapped in the chromosphere plasma. These field lines extend roughly perpendicular from the solar surface, but, as the Sun turns, the lines which leave the surface radially arc into Archimedian spirals. Given the average solar wind velocity (along with which the lines propagate), and the 27-day rate of solar rotation, the field lines at 1 AU are bent 45° from the Sun-Earth direction; they may be positive at 135° and negative at 315° , or vice versa. Particle velocity fluctuations are characteristically anisotropic about the bulk velocity. Fluctuations parallel to the magnetic field are greater than perpendicular fluctuations, leading to a temperature anisotropy of the solar wind $T_{\parallel} \approx 2T_{\perp}$.

The spiral structure of the magnetic field is one manifestation of what is termed the "macrostructure" of the solar wind. The structure is divided into positive and negative regions (depending upon whether B is positive toward 135° or toward 315° , respectively) called sectors. Typically 4 to 6 sectors (always an even number) exist around the Sun. Smaller scale features in the velocity and magnetic structure are called "mesostructure" and include the flux tubes which conduct solar flare particles. Still smaller scale structure, the "microstructure" creates magnetic opacity which reduces the flux of interstellar cosmic rays. The average solar field strength at the orbit of Mars is thought to be about 2γ , but the instantaneous value may range up to 25γ . The larger field values - and abrupt changes in direction of field lines - are associated with hydromagnetic shock waves passing through the solar wind plasma.

Martian Magnetosphere and Magnetic Moment

A planet's magnetic field is expected to be bounded on the sunward side by currents flowing in the solar wind plasma (q.v.). The field is thus confined to a roughly teardrop-shaped cavity known as the magnetosphere. The boundary of the magnetosphere (magnetopause) is a surface along which, roughly speaking, the planetary magnetic field pressure ($B^2/8\pi$) is balanced by the effective pressure of the solar wind directed flow. "Radiation belts" of energetic electrons and protons are expected to be contained within the magnetosphere.

The magnetosphere forms an obstacle to the solar wind flow. Because this flow is "supersonic," a shock wave (bow shock) is expected to be formed in the flow ahead of the magnetosphere and to be readily detectable as a surface of discontinuity in plasma and field parameters.

The Mariner IV instruments gave no indication of any effects associated with a Martian magnetosphere, its radiation belts (Van Allen et al., 1965), or its associated bow shock (Smith et al., 1965). This fact, interpreted in terms of appropriately scaled terrestrial magnetospheric parameters, was used to set a limit on the possible sunward projection of the bow shock (at $0.6 R_M$ above the surface) and thus to set an upper limit on the Martian magnetic moment.

Even if Mars has little or no intrinsic magnetic field, it may be expected to have a bow shock, located about one-third planetary radius sunward from the planet's surface. The effective "magnetosphere" is created by induced currents in the Martian ionosphere that "pile up" interplanetary fields carried by the solar wind flow. (Venus has been found to possess such a bow shock, Bridge et al., 1967.)

Surface Magnetic Fields

The Mariner IV data would permit an intrinsic surface (dipole) field as large as 100γ and a magnetosphere extending to about $0.5 R_M$ above the surface on the sunward side (Smith et al., 1965). A diurnal field variation produced by currents at the magnetopause would evidently be observable at the surface.

For an intrinsic magnetic field less than about 35γ , the ionospheric currents would replace the magnetopause with an "ionopause" (Bridge et al., 1967) and time-variable fringing fields, of the compressed interplanetary fields of about 35γ , would be expected on the surface near the subsolar point, dropping to interplanetary values or less past the terminator.

6.3 THE METEOROID ENVIRONMENT

Most of what is known about the present-day meteoroid flux in the solar system is derived from terrestrial and the near-1 AU spacecraft observations, although Mariner II carried a "cosmic-dust experiment" to Venus and Mariner IV carried one to Mars. The observations include eye-witness accounts of meteorite falls, photographic records of meteors in flight, radar observations of ionization trails, photometry of the zodiacal light, detection of space-induced radioactivity in particles from ocean sediments and polar ice, and spacecraft penetration and acoustical measurements.

A meteoroid is a solid particle in space. A meteor is the electromagnetic phenomenon produced when a meteoroid penetrates the atmosphere. A bolide is a sound-producing meteoroid. The term meteorite is reserved for meteoroidal objects which have fallen to the Earth. Each meteoroid, no matter how small a particle, maintains its own orbit about the Sun until it is deflected by a perturbing gravitational field, degraded by radiation drag (Poynting-Robertson effect), swept away by radiation pressure, or until the particle is destroyed either by collision with another, or by sputtering or evaporation. New meteoroids constantly replace those being destroyed. The source of meteoroids may be from any one or a combination of the following: abrasion or collisions of asteroids, fragmentation of comets, condensation of gaseous atoms and molecules, or the capture of interstellar dust by the solar system.

Most meteoroids trace direct orbits about the Sun. Those with Earth-crossing orbits have semimajor axes both larger and smaller than 1 AU, and most have rather large eccentricities. The larger percentage of meteoroids overtake the Earth, enter its atmosphere nearer the antapex and are thus more frequent in the evening. Those with a semimajor axis less than 1 AU are overtaken by the Earth and are slightly more frequent during the morning hours. Retrograde meteoroids are less common and enter the leading hemisphere with low frequency and great velocity. Statistics indicate there are two families of meteoroids, designated sporadic and stream meteoroids. The sporadic meteoroids, whose orbits have elements which vary but are similar, appear randomly in the Earth's sky. Stream meteoroids of any one stream have nearly identical orbital elements. The sources of sporadic meteoroids are still subject to speculation, while the source of many meteoroid streams is clearly related to short and long period comets.

Comprehensive reviews of the nature of meteoroids and their flux have been written by Whipple (1967), Kaiser (1968), Singer (1969), Dohnanyi (1969), and Whipple et al. (1969). More recent considerations based on spacecraft experiments have been set forth by Gerloff and Berg (1970) and are concerned primarily with the terrestrial and lunar environments. Extrapolation of this

data to Mars is solely dependent upon Mariner IV results for reference. The Mariner IV results indicated a five-fold increase in dust particle flux at 1.4 AU (from $7.3 \times 10^{-5} \text{ m}^{-2} \text{ sec}^{-1}$ to $3.3 \times 10^{-4} \text{ m}^{-2} \text{ sec}^{-1}$), and then a decrease to $1.8 \times 10^{-4} \text{ m}^{-2} \text{ sec}^{-1}$ at encounter with Mars (Alexander, McCracken, and Bohn, 1965). These results apply only to dust. Whether they have any relevance to larger sporadic material is uncertain. In general, the meteoroid streams intersected by Mars' orbit are different from those encountered by Earth. There is no reason to expect the flux in the Mars intersected streams to be grossly different from those intersecting the Earth's orbit. Velocities of meteoroids further from the Sun will be somewhat lower. Sporadic meteoroids and stream meteoroids obey different flux laws near Earth. These laws are derived from the photographic, radar, and spacecraft experiments previously described. Models of these mass-flux laws are presented in Fig. 3. Figure 3 shows the most important experimental points as well as the models developed by Dohnanyi (1969) and Whipple et al. (1969). Stream meteoroids are seen to have a much flatter mass-flux function, resulting in their being overwhelmed by sporadic meteoroids at low mass. The mass cutoff at $\sim 10^{-12} \text{ g}$ represents the removal of very small particles by radiation and solar wind pressure, and the decreasing slope between 10^{-8} g and 10^{-12} g reflects the reduced lifetimes of smaller particles due to radiation drag, collision, and sputtering. The frame of reference is the geocentric frame. The flux presented in Fig. 3 is that which a massless observer would experience while traveling in a near circular orbit at 1 AU. The effect of Mars gravity is to focus those meteoroids having low areocentric velocities, thus increasing the flux somewhat. In addition, Mariner IV found a factor of 2 to 3 increase in flux for sporadic meteoroids.

An encyclopedic statement, even about geocentric meteoroid velocities, is impossible to make at this stage in our experimentation. It is difficult to determine whether the difference in velocities with mass represents real variations in meteoroids, or differences in the methods of measurement. Stream meteoroid velocities can be rather accurately determined because many meteoroids of each stream are available for measurement. The eighteen major streams encountered by Earth have geocentric velocities ranging from 16 km sec^{-1} to 72 km sec^{-1} and averaging about 40 km sec^{-1} . The Earth's orbital velocity plus the maximum rotational component is roughly 30.2 km sec^{-1} . The difference, 42 km sec^{-1} , is virtually the parabolic velocity (escape velocity) at Earth's distance from the Sun. This indicates that many meteoroid orbits are of large eccentricity; in fact, all but one of the eighteen major streams encountered by Earth have eccentricity greater than 0.75 (Whipple et al., 1964).

The mean orbital velocity plus the maximum rotational component of Mars is roughly 24.3 km sec^{-1} and the parabolic velocity at its mean distance is 34 km sec^{-1} . Therefore, Mars can be expected to encounter streams with relative velocities between about 10 km sec^{-1} and 58 km sec^{-1} .

The geocentric velocities of sporadic fireballs range typically from near zero to about 30 km sec^{-1} and average about 15 km sec^{-1} (McCrosky, 1968). The fireball orbits tend to display low to moderate eccentricities and perihelia slightly smaller than 1 AU. Radar observations of much smaller objects show

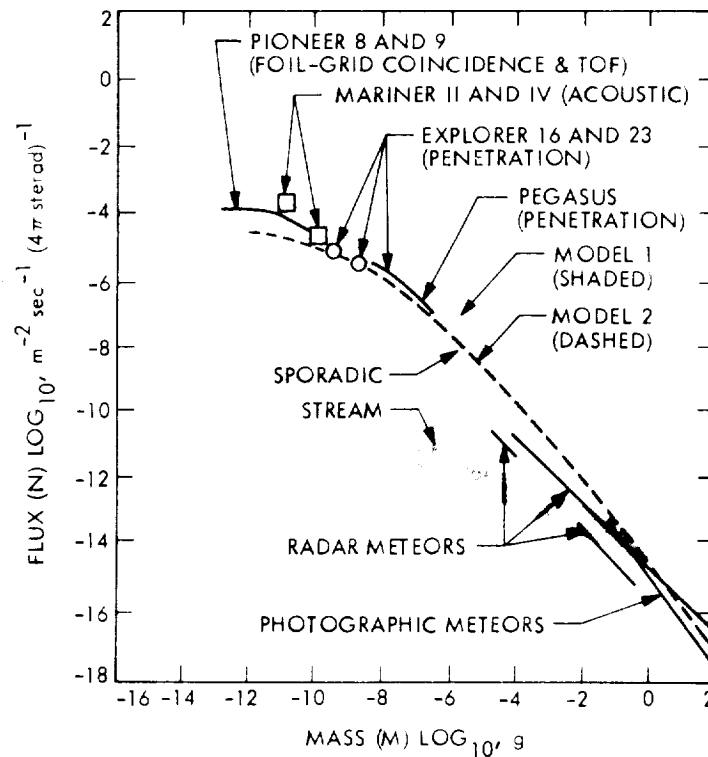


Fig. 3. The mass-flux relationship. The flux is that observed near 1 AU in the absence of gravitational focussing. (Adapted from Berg and Gerloff, 1970a.)

semimajor axes ranging from 0.4 to >5 AU, with the number of objects increasing with increasing eccentricity, and having more or less random inclination. Further, geocentric velocities range from very low to extremely high ($\sim 70 \text{ km sec}^{-1}$) with an average around 40 to 50 km sec^{-1} . Most of the very small objects measured by Pioneers 8 and 9 (Berg and Gerloff, 1970a and 1970b) had low geocentric velocities and semimajor axes <1 AU. (One was retrograde, semimajor axis less than 1 AU; one was direct, semimajor axis approximately 3 AU.) This observation is interpreted by the authors to reflect radiation drag on the very small particles, reducing their large, highly eccentric orbits to small, less eccentric orbits.

Barring an encounter with an extra-solar system body (a hyperbolic meteoroid*), the velocities of sporadic meteoroids near Mars must also be in the range of 10 to 58 km sec^{-1} . However, the distribution of sporadic meteoroids within that range is unknown.

*The existence of hyperbolic meteoroids is speculative and not commonly accepted by all experts.

Bulk density of photographic objects may be calculated from drag theory and the photometric mass equation (McCrosky, 1968). No photographic object has yielded a bulk density greater than 1.2 g cm^{-3} , with the average about 0.4 g cm^{-3} . However, Pribram meteorite, whose photographic density was small, had a measured bulk density of 3.5 g cm^{-3} . The uncertainty remains as to whether our understanding of drag and ablation is in error, or whether that part of Pribram which reached the ground represented only a small, dense fraction of the whole meteoroid. The latter hypothesis is widely accepted, and the density of most meteoroidal material is considered to be $\leq 1 \text{ g cm}^{-3}$.

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DOCUMENT CONTROL LIST

These pages, together with the dividers and the two Mars maps (I. P. P. Mars 1969 and MM'71 Mars Planning Chart in the pocket on the inside-front cover), form the total content of the document as revised, publishing date March 1, 1972.

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CHANGE NOTICE
MARS SCIENTIFIC MODEL REVISION

The attached material replaces and/or supplements the information contained in the Mars Scientific Model, Document No. JPL 606-1, published July 15, 1968. The revised material reflects data obtained and/or derived from Mariners 6 and 7, and other sources available through March, 1972.

INSTRUCTIONS FOR UPDATING

MAPS: Place the two new Mars maps (IPP Mars 1969 and MM'71 Mars Planning Chart) into the map pocket located inside the front cover. Discard maps MEC-1 and MEC-2.

FRONT MATTER: Replace entirely with new issue of Front Matter except for color Frontispiece (to remain as page iii).

SECTIONS 1 and 2: Replace entirely with new issues of Sections.

SECTION 3: Replace Contents pages with new issue of Contents.

SUBSECTIONS 3.1, 3.2, 3.3, 3.4: Replace entirely with new issues of Subsections.

SUBSECTION 3.5: Replace entirely with new issue of Subsection except: Retain p. 29* (Fig. 24) and insert as last page of Subsection.

SUBSECTION 3.6: Insert new Tab and new Subsection 3.6.

SECTION 4: Replace Contents pages with new issue of Contents.

SUBSECTION 4.1: Replace entirely by new issue of Subsection.

SUBSECTION 4.2: Replace entirely with new issue of Subsection except: Retain pp. 19*, 21*, 23* with related color maps and overlays, and p. 25* (replacing overlay of Place-Names with new one) and insert as last pages of Subsection.

SECTION 5: Replace Contents pp. 1 thru 3 with new issue of Contents (i thru iii), and retain p. 5* as the last page.

SUBSECTIONS 5.1 and 5.2: Replace entirely with new issues of Subsections.

SUBSECTION 5.3: Retain entire Subsection except: Replace pp. 21* and 23* with new p. 21 and insert new p. i in front of Subsection.

SUBSECTION 5.4: Retain entire Subsection except: Replace pp. 19* thru 22* with new pp. 19 thru 21 and insert new p. i in front of Subsection.

SECTION 6: Replace entirely with new issue of Section.

APPENDIX: Replace with new Appendix (Document Control List).

Verify contents of total updated Mars Scientific Model Document
by use of this new Document Control List.

* Denotes page numbers of material retained from original (1968) issue of Mars Scientific Model Document.

